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WASTE HEAT UTILIZATION IN WASTEWATER TREATMENT

Franklin J. Agardy, et al

URS Research Company

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WASTE HEAT UTILIZATION IN WASTEWATER TREATMENT

by

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for

Office of Research and Monitoring
ENVIRONMENTAL PROTECTION AGENCY

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16. Abstract

The technical and economic feasibility of using waste heat to improve conventional and advanced wastewater treatment processes was investigated. Important sources of waste heat were identified and the effects of increased temperature on wastewater treatment processes were explored.

A cost/benefit analysis indicated favorable application of waste heat in conventional wastewater treatment plants adjacent to heat sources where at least treatment is employed and the capacity is greater than 5 MGD. Benefits were also shown in advanced treatment processes of reverse osmosis, carbon adsorption and ion exchange. (EPA)

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ABSTRACT

The technical and economic feasibility of using waste heat to improve conventional and advanced wastewater treatment processes was investigated in a desk top study. Important sources of waste heat were identified, especially in low temperature areas. The effects of increased temperature on wastewater treatment processes were explored.

The cost/benefit analysis indicated favorable application of waste heat in conventional wastewater treatment plants adjacent to heat sources where at least secondary treatment is employed and the capacity is greater than 5 MGD. In such cases, benefits exceed costs from 0.2 to 0.9 cents/1000 gal. However, these cost benefits will be less if fouling of heat transfer surfaces is greater than anticipated in this report.

The advanced treatment processes showi[illegible]ghest benefits from waste heat use were reverse osmosis, [illegible]sorption, and ion exchange. These unit operations have [illegible]ngs ranging from 1.6 to 9.4 cents/1000 gal for 1 MGD plants and 0.8 to 7.3 cents/1000 gal for 10 MGD plants.

The utilization of waste heat to increase the temperature during nitrification would have the effect of decreasing the required aeration tank volume, hydraulic detention time and oxygen requirement in addition to carbonaceous oxidation.

This report was submitted in fulfillment of Project Number 17090GAF, Contract 68-010013, under the sponsorship of the Environmental Protection Agency.

FOREWORD

This report summarizes research conducted by URS Research Company for the Federal Water Quality Administration, Department of the Interior, under Contract No. 68-01-0013 during the period of December 31, 1970 through June 30, 1972. The work was prepared under the direction of Dr. Franklin J. Agardy, Vice President and Director of the Environmental Systems Division. The research team was comprised as follows:

M. Fields - Project Officer

M. Staackmann - Senior Research Chemical Engineer

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SECTION I

CONCLUSIONS

1. Heat transferred from utility waste to waste is not a means for thermal pollution control. It does reduce the thermal shock to receiving body and produce subsequent beneficial uses.

2. The total waste heat lost from industrial operations in a usable form during 1970 is as follows:

   heated cooling water - 7.7×10^{15} BTU

   hot exhaust gases - 1.5×10^{15} BTU

3. Waste heat in the form of power plant cooling water discharge is the largest source of such heat and amounts to about 83% of all waste heat lost from industrial operations. However, it is limited by the low level of heat normally available and the seasonal variations in output.

4. Use of waste heat in the form of heated water is economically more feasible than the use of hot exhaust gases, except for special applications.

5. Far northern areas (such as Alaska) differ significantly from the United States average in power plant usage as indicated below:

   - A much higher fraction of the total electric power is generated with natural gas turbines and diesels which emit waste heat in the form of hot exhaust gases.

   - The power demand seasonal variation is unimodal with the peak in the winter months.

6. The grouped utility concept appears to be very favorable for the electric power/wastewater treatment combination owing to the savings in transport costs of from 1 to 45 cents/1000 gal of wastewater treated.

7. Several methods of heat transfer appear feasible for use in improving wastewater treatment plant efficiency, depending on whether heated water or hot exhaust gas is available. The feasible methods include rotating disc, double-pipe, plate and frame, shell

and tube, plate and cooling tower or trickling filter heat exchangers. The effects of fouling due to wastewater contaminants (especially organics) are unknown and can radically change the feasibility of heat transfer methods.

8. The effect of increased temperature appears to be beneficial for conventional and advanced wastewater treatment processes with potential cost savings of from 1 to 10 cents/1000 gal of wastewater treated.

9. The benefit/cost evaluation reveals that waste heat application is profitable only for plants where at least secondary treatment is employed. In addition, the most advantageous conditions are for plants with capacities above 5 MGD and where the distance which the waste heat must be transported is short (less than a mile).

10. The benefit/cost evaluation for advanced wastewater treatment reveals that several of the processes can utilize waste heat profitably, even where the entire treatment plant consists only of a single process; namely, reverse osmosis, activated carbon adsorption, and ion exchange. Treatment plants using other processes would profit from waste heat use only where the plants consist of a number of processes operating in series.

11. It is feasible to accomplish nitrification in the same aeration tank as the one used for the activated sludge process due to the effect of increased temperature from the waste heat utilization. An increase of temperature of 5°C above the base temperature (10°C) has the effect of decreasing the required aeration tank volume and hydraulic detention time by 24 percent while reducing the oxygen requirement in addition to carbonaceous oxidation by 12 percent.

12. The dynamics of fouling due to wastewater contaminants, especially organics, are relatively unknown. With new research and improved technology, heat transfer methods could be modified to increase existing benefits from waste heat utilization.

SECTION II

RECOMMENDATIONS

1. The use of hot exhaust gases as a waste heat source should be investigated, especially to ascertain the heat transfer potential in a direct contact system and to explore the possibility of using a hot gas environment over selected treatment processes. Certain pretreatment may be required, depending on the nature of contaminants in the hot gases.

2. The grouped utility concept should be studied in more detail to consider the possible inclusion of other industries to maximize benefits.

3. Whenever waste heat in the form of hot water is being used and the hot water must be transported over a distance greater than a mile, a pipeline should be employed, with careful attention given to heat losses.

4. A temperature-sensitive activated sludge and secondary clarification model should be developed to (a) theoretically discern and test those parameters which affect the processes singly and collectively (other than percentage BOD removal) and (b) compare those theoretical productions with field data to determine the optimum operating mode and the costs that would be associated with it.

5. The effects of temperature on chlorination should be explored to determine if an optimum dosage and contact time can be combined to obtain a better contact chamber design and kill efficiency.

6. A number of conventional (at least secondary treatment) and advanced waste treatment plants across the country should be examined to identify specific local waste heat sources and the benefit/cost relationship for application of waste heat.

7. A study should be conducted to investigate the full spectrum of benefits to power plants which would result from waste heat utilization. Of particular interest would be the potential savings to the power plant due to a lower effluent temperature mixing with the treatment plant discharge. Whereas the total heat discharged to the receiving water may not be reduced significantly, the reduced thermal shock may be of value and mixing zone areas are decreased in the receiving water.

8. Additional work should be done to define more precisely the temperature effects on parameters of nitrification, especially the rate constants which take place during the latter stages of carbonaceous oxidation.

9. The most important area where more information is needed is the effect of organic fouling for 10 C increase in wastewater temperatures or where heat is transferred to increase wastewater temperature to 30 C. This fouling can greatly affect the benefit/cost evaluations on the type of heat exchanger units proposed in this desk top study. Pilot plant and/or field studies should be conducted.

SECTION III

INTRODUCTION

The overall objective of this desk top study (evaluation of technical reports and other available data) was to investigate the technical and economic feasibility of utilizing waste heat to improve wastewater treatment process efficiency, emphasizing use in cold climate areas. Recognizing that maximum benefits probably would be obtained in new facilities, particular attention has been given to the grouped-utility concept wherein the costs for transporting the waste heat are minimized.

The treatment of domestic and industrial wastes generally takes place at ambient temperatures due to the large quantities of wastewater involved. However, it is recognized that most physical, chemical and biological processes operate with greater efficiency at elevated temperature (10-30 C). Conversely, most processes, particularly those of a biological nature, are severely curtailed at low temperatures, precluding their use in very cold climates (e.g., where wastewater temperatures are in the 0-5 C range). Two general alternative solutions are available:

- Raising the temperature of the water to a level where adequate biological activity can take place
- Adopting physical and/or chemical treatment methods which are less sensitive to temperature.

The high cost of heating wastewater has traditionally precluded the former.

During the past several years an increasing public concern has developed regarding the problems of thermal shock on watercourses created by waste heat discharged from power generation and industrial processes. For the most part, this heat is in the form of warm to moderately hot cooling water (30-50 C or 86-122 F) whose temperature is not high enough to be of further economic value to the discharger. Additionally, large quantities of waste heat are discharged to the atmosphere from power plants, industrial facilities, incineration, etc. Recognizing that warm water represents a sizable resource of low-cost heat, the possibility of locating utilities (power and wastewater treatment) to maximize heat transfer offers an attractive solution to problems of wastewater treatment in new facilities located in cold climates.

In order to establish a flexible work effort, this "desk top" project was divided into three phases:

I Heat Resources and Heat Transfer

II Temperature Effects on Activated Sludge and Ancillary Support Processes

III Temperature Effects on Advanced Waste Treatment Processes

PHASE I

The heat resources and transfer portion of the study was designed to assess the availability of information for determination of candidate sources of waste heat in terms of available quantity, temperature and seasonal variation. This included the projected population expansion and related industrial and power plant development in the Far North.

A review of applicable heat transfer mechanisms, hardware and associated transfer efficiencies was conducted during the first phase of this work. Along with this, power plant technology was studied to identify any limiting aspects in adaptability, and delineate any anticipated attendant problems and limitations to the grouped-utility concept.

PHASE II

This phase of the project concentrated on the effects of temperature on the activated sludge process and selected ancillary operations. Consideration was given to change in performance characteristics and their effects on economics of plant operation in cold climate regions. As part of this effort a literature review was conducted to assess the availability of data on temperature coefficients, biological reaction rate constants for activated sludge, and the effects of temperature on settling, chlorination and other processes.

An informal data sheet was sent to various cities (see Appendix A) which were determined to be in cold climate regions. Information from these cities provided actual treatment plant performance and allowed the establishment of realistic temperature ranges for the operation of activated sludge systems and ancillary units.

Points within the process scheme were selected at which waste heat could be added to optimize the beneficial effects of operating at higher temperatures, utilizing the candidate heat transfer mechanisms developed in Phase I.

A preliminary mathematical computer model was developed to reflect the temperature dependency of the activated sludge unit to waste treatment efficiency parameters.

Anticipated operational problems, detrimental effects, incremental capital, and operating and maintenance costs from either heating the wastewater or from operating at elevated temperatures were also reviewed to present the operational characteristics and determine the economic feasibility of an activated sludge/wastewater treatment plant under imposed conditions.

PHASE III

Various advanced wastewater treatment processes were examined to determine the feasibility of their operation at elevated temperatures. This feasibility study encompassed technical, operational, and economic factors. Wherever possible, mathematical relationships for performance characteristics and feasibility elements are presented.

A wide range of candidate advanced wastewater treatment processes was considered with emphasis being placed on those aimed at nutrient removal. In general, the evaluation of temperature effects on the processes of interest was restricted to a temperature range of from local ambient to about 10 C above ambient (to correspond to the average temperature increase deliverable from discharged cooling water in electric power generating plants).

SECTION IV

LITERATURE REVIEW

PHASE I

A review of literature was conducted to determine the character of candidate sources of waste heat in terms of available quantity, temperature, seasonal variation, etc. Some of the sources considered were fossil fuel and nuclear power plants, heavy industrial processes, and waste incineration.

Table 1 is a matrix of the distribution of various references as they apply to heat transfer mechanisms, sources of heat and general thermal considerations. The data matrix reveals that the greatest availability of information concerns heat transfer mechanisms, while the data on economics of heat transfer and effects of thermal shock are limited. Information on effects of thermal pollution on the aquatic environment, the economic aspects, specific sources and mechanisms are also included in the bibliography of Appendix B.

Table 1

PHASE I DATA MATRIX

INFORMATION AREA	HEAT TRANSFER	HEAT SOURCES	GENERAL THERMAL CONSIDERATIONS
Nuclear power	116	121,85,116,51,56,159, 57,24,151,121,85,53,	
Fossil fuel	69,102,112	51,75,162,102,87, 159,57,151	53,51,57
Industrial processes	112	85,23,118	51,57,118
Effect on environment		156,86	121,84,156,91, 32,86
Economics	58,97	58,97	95,162,58,97,92
Mechanisms	46,14,38,11,63, 69,123,59,112,60, 148,95,162,159,126, 86,150,155,4,163	60,23,37,24	14,42,11,147,59, 60,75,162,167,23
Miscellaneous		102,126,86	121,166,42,59,53, 78,152,33,88,92,37

PHASE II

A literature search was conducted to obtain information (particularly quantitative expressions) concerning the temperature dependency of the activated sludge process and various ancillary unit operations.

Table 2 is a data matrix which indicates the distribution of various references as they apply to temperature coefficients, biological reaction rate constants for activated sludge and the effects of temperature on settling, flocculation and chlorination. Reference data concerning the operational problems and economic impact of wastewater treatment plants at elevated temperatures are also shown. The numbers in the matrix are the reference numbers as they appear in the bibliography of Appendix B.

Table 2

PHASE II DATA MATRIX

INFORMATION AREA	BIOLOGICAL SYSTEMS	ANCILLARY PROCESSES	GENERAL CONSIDERATIONS
Temperature coefficients	10,110,48,34,44, 16,136	6	139,110,60,16
Biological rate constants	10,48,34,45,16, 111,138,136,79		73
Temperature effects-dynamics	140,117,20,26, 48,16,98,138, 120,70,153,21, 136,43,30,79,80	52,157,68, 54,25,28,129, 27	140,110,114,34,98, 16,153,52,160,43, 9,26
Economics		66,34,120	68
Miscellaneous	70,98		82,72,74,5,21,31, 105,129,89,101

PHASE III

A review of applicable literature was conducted to establish the state of the art concerning candidate advanced wastewater treatment methods. The primary concern of this review was to obtain performance characteristics over the temperature regime of interest in waste heat utilization.

A matrix of the distribution of the references as they apply to the various treatment methods and important characteristics is given in Table 3. A bibliography covering this literature review is given in Appendix B.

Table 3

PHASE III DATA MATRIX

TREATMENT METHOD	PERFORMANCE DATA	COST DATA	GENERAL INFORMATION
Reverse osmosis and electrodialysis	1,71,2,45,134,3, 36	71,2,104, 3,113	2,45,43,83
Activated carbon and foaming	76,1,2,3	2	76,2
Ion exchange	73,1	73,104	83,73,2
Ammonia stripping	1,2	2,3	146,2,3
Denitrification	109,3,35	3	2,109,3
Chemical clarification	139,127,128,2,3	139	139,2
Phosphate removal	139,3	139,3	139,115,2,3
Freezing	2	2,113	2
Distillation	2	113	2,149

SECTION V

SOURCES OF WASTE HEAT

On the basis of the extensive literature review, it is possible to characterize the various candidate sources of waste heat. In this section, these waste heat sources will be delineated with respect to importance (i.e., total quantities of heat available for use), and then aspects relating to the potential application of this waste heat will be discussed.

MAGNITUDE OF CANDIDATE WASTE HEAT SOURCES

The most important sources for this study will probably be heated water discharges since they represent the greatest magnitude of heat and are extremely easy to transport and utilize. In some cases, hot exhaust gases are also very significant and such cases will be identified. Heated water discharges are primarily the cooling waters resulting from various industrial and municipal plants. The largest users of cooling water on a nationwide basis[121] are indicated below by industrial category:

INDUSTRIAL CATEGORY	PERCENTAGE OF TOTAL COOLING WATER USE
Electric power generation	81.3
Primary metals manufacture	6.8
Manufacture of chemical & allied products	6.2
Manufacture of petroleum & coal products	2.4
Manufacture of paper & allied products	1.2

No other single category represents as much as 1% of total cooling water use.

Based on statistics from the power generation industry,[85,86,126] cooling water requirements can be converted into BTU's of thermal energy discharged.* Waste heat in the form of heated water discharges can now

*Industry statistics are given in units of water flow (e.g., gallons per minute). The temperature increase for such water averages about 10°C for this industry. The water flow rate and temperature increase can then be combined to yield the thermal discharge in BTU's.

be itemized for industrial categories in terms of BTU per year as shown in the following table:

MAJOR INDUSTRIAL CATEGORY	HEATED WATER WASTE HEAT (BTU/yr)
Electric power	5.30×10^{15}
Primary metals	0.44×10^{15}
Chemicals & allied products	0.40×10^{15}
Petroleum & coal products	0.16×10^{15}
Paper & allied products	0.08×10^{15}
MAJOR INDUSTRY TOTAL	6.4×10^{15}

By adding additional waste heat to this total to account for minor industries not shown above and to reflect the fact that some industries discharge more heat per unit of cooling water than the power generation industry, it is estimated that the total for all heated water discharges amounted to 7.7×10^{15} BTU for 1970.

The hot exhaust gases associated with industrial operations can also be quantified in terms of waste heat available for use;[86,126] these figures are given below for 1970:

MAJOR INDUSTRIAL CATEGORY	HOT EXHAUST GAS WASTE HEAT (BTU/yr)
Electric power	1.11×10^{15}
Primary metals	0.092×10^{15}
Chemicals & allied products	0.084×10^{15}
Petroleum & coal products	0.033×10^{15}
Paper & allied products	0.016×10^{15}
MAJOR INDUSTRY TOTAL	1.3×10^{15}

Taking into account industries not shown above, it is estimated that hot exhaust gas waste heat amounted to 1.5×10^{15} BTU for 1970. When combined with the heated water waste heat, the overall total waste heat for 1970 is estimated at 9.2×10^{15} BTU.

Another candidate source of waste heat which has been considered is the growing collection of radioactive nuclear wastes.[56] This source consists of the wastes from nuclear weapon production and nuclear electric power generation. With the projected growth of nuclear power,[56] the associated wastes are estimated to be 1.2 billion curies or more per year by 1990. Using a conversion factor to indicate the heating capability for typical radioactive elements,[24] the 1.2 billion curies would yield an equivalent of 3.6×10^{12} BTU/year. A heat source of this magnitude is rather insignificant in comparison with other sources indicated above, but could be important for a few localized areas or in the future when more radioactive wastes are available.

TEMPERATURE AND SEASONAL VARIATIONS

The temperature of discharged cooling water from industrial processes depends on a number of factors such as the temperature of the inlet water, the operating conditions of the process being cooled, and the local restrictions concerning thermal discharges. For electric power plants using ambient temperature groundwater for cooling by the once-through method, the discharged water will be warmed from 5 to 15 C above ambient. In such plants the cooling water is used to condense steam at fairly low temperatures since the steam is discharged from the turbine at low pressures to achieve the desired thermal efficiencies in the plant. For other types of industrial plants, the cooling water is used for process boilers, waste heat boilers, and chemical recovery units. In some of these plants the cooling water is used to condense steam at higher pressures than the power plant turbine discharge steam, and the discharged water may be warmed as much as 50 C above ambient. Since electric power generation contributes the bulk of heated cooling water, most of this water will, therefore, be available in the range of 5 to 15 C above ambient and at absolute temperatures in the range of 25 to 40 C.

The temperature of hot exhaust gases from combustion and chemical processes depends on such factors as combustion efficiency, process operating conditions, and the amount of in-plant heat recovery which is utilized. In electric power plants, the exhaust gases pass through economizers, air preheaters, and air pollution control devices and are generally discharged at between 100 and 250 C. In almost all industrial processes, heat recovery from exhaust gases is used and discharge temperatures will be in approximately the same range.

The seasonal variations in waste heat generation will be reflected by the normal demand variations for the products of the various industries. In the case of electric power generation,[53] the demand cycle over the year has two peaks, one corresponding to the winter heat demand and the other (much higher) corresponding to the summer air conditioning demand. This seasonal variation of demand for electric power in the United States is shown graphically in Fig. 1.

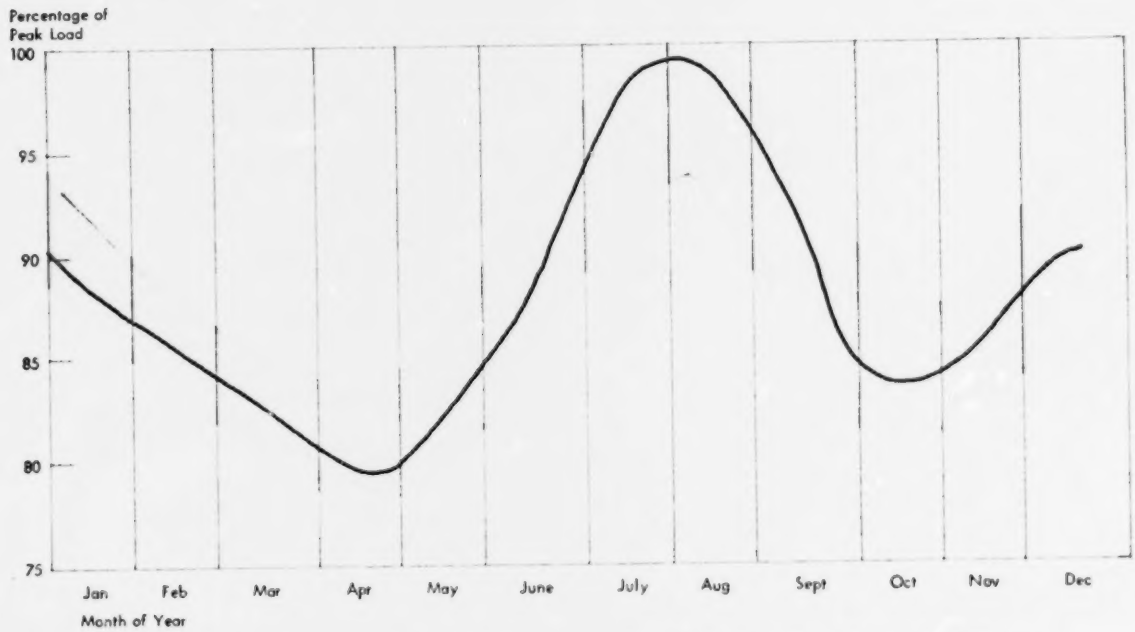

Fig. 1. Seasonal Variations in Electric Power Demand

DIFFERENCES BETWEEN TYPES OF POWER PLANTS

There is a marked difference between the magnitude of heated water discharges from fossil-fueled vs nuclear electric power plants.[86,126] Fossil-fueled plants operate at about 38% thermal efficiency with current technology. Nuclear plants now in use operate at lower steam temperatures and pressures with resultant lower thermal efficiencies (about 33%). The overall result is that present nuclear plants discharge about 40 to 50% more heat per unit of electricity generated

than the average of fossil-fuel plants now in operation. With the development and use of breeder reactors, it is anticipated that plant efficiencies will approach those of new fossil-fuel plants.

Owing to the nature of nuclear power plants, hot exhaust gases are virtually eliminated and this source of waste heat is nonexistent for such plants.

SECTION VI

INFORMATION CONCERNING THE FAR NORTH

It has been anticipated that the Far North will be a likely area for application of waste heat to improve wastewater treatment process efficiency. For this reason, appropriate information concerning Alaska and the cold weather regions has been gathered. Details for Alaska are given first and information on other areas follows.

POPULATION STATISTICS

Alaska has experienced rapid population growth in the past 20 years. Population figures by decade are given below:

1950	129,000
1960	226,000 (76% higher than 1950)
1970	294,000 (30% higher than 1960)

Although rapid growth in continuing, the percentage increase in population for the 10-year period to 1970 is not as great as for earlier periods. Projections for the 1975 Alaskan population vary from 310,000 to 340,000. The larger number assumes that the percentage increase for the last decade will continue unchanged into the future.

There are only four incorporated cities within Alaska with populations in excess of 5000; these are shown below:

CITY	POPULATION		PRESENT CHANGE
	1970	1960	
Anchorage	46,100	44,200	+ 4.3
Fairbanks	14,300	13,300	+ 7.7
Ketchikan	6,700	6,480	+ 3.4
Juneau	6,000	6,800	- 11.7

There are only 17 other cities in Alaska with a population exceeding 1000.

It appears that by 1975 there will still be only four cities with populations above 5000. Reasonable projections for these cities would assume that percentage increases in the future are no more than about twice those of the past and population declines (as for Juneau) would be reversed to yield perhaps a 5% increase in 10 years. Population projections for these cities in 1975 are:

Anchorage	48,000
Fairbanks	15,400
Ketchikan	6,900
Juneau	6,300

The locations of these major cities and the regional areas of Alaska are shown in Fig. 2.

Fig. 2. Cities and Regional Areas of Alaska

INDUSTRIAL AND POWER PLANT DEVELOPMENT

Two factors concerning Alaska give importance to waste heat in the form of heat exhaust gases. First, the production of natural gas in the South Central Region (see Fig. 2) has resulted in the high use of natural gas turbines with almost all waste heat given off as exhaust gas. Second, the majority of remote towns and villages in Alaska are widely separated and not on an interconnecting grid. This combination of factors has produced a reliance on diesel power for energy and here again most of the waste heat discharges are hot exhaust gases.

Due to the cold temperatures and the high transportation and fuel costs in Alaska, waste heat from power plants is currently used for heating buildings and potable water supplies.

Current cooling water usage for Alaskan industry is 43.5 million gallons per day (MGD). Of this total, 20.65 MGD is used in the South Central Region (vicinity of Anchorage) and 9.85 MGD is used in Ketchikan; the remaining 13.0 MGD is being used in Sitka. Projected cooling water usage is 140 MGD, with 9 MGD for Fairbanks, 13 MGD near Anchorage, 48 MGD near Juneau and 35 MGD for Ketchikan.

Current power plants associated with the four major cities are as follows (waste heat figures were obtained directly from power companies):

Fairbanks Area

1. 9.5 Mw plant, 84 million BTU/hr heat rejected,* 56 gal/kwh cooling water
2. 30 Mw plant, 265 million BTU/hr rejected, 10 gal/kwh cooling water
3. 2 diesel plants, 40 Mw total, 518 million BTU/hr rejected, all heat lost to air
4. 22 Mw plant, 193 million BTU/hr rejected, some cooling water used for heat, 2 miles south of Fairbanks

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*The heat rejection values refer to waste heat discharged in the form of water or air heated above the local ambient temperature.

5. 15 Mw plant, 140 million BTU/hr rejected, some cooling water used for heat, 26 miles south of Fairbanks

6. 22 Mw plant, 193 million BTU/hr rejected, some cooling water used for heat, 50 miles southwest of Fairbanks

7. 22 Mw plant, 193 million BTU/hr rejected, 25.5 gal/kwh cooling water, 50 miles southwest of Fairbanks.

Proposed power plants and industry for these cities are as follows:

Ketchikan Area

15 Mw plant, 133 million BTU/hr rejected, 44 gal/kwh cooling water

Fairbanks Area

1. Power plant addition (unspecified)
2. Oil refinery and power plant
3. Oil refinery

Anchorage Area

1. Power plant expansion
2. Cement plant proposed north of Anchorage
3. Increased natural gas output (Kenai)

Juneau Area

1. Pulp mill 50 miles north of Juneau
2. Pelletized iron ore 50 miles southeast of Juneau

Ketchikan Area

Copper mine on Gravian Island (near Ketchikan)

SEASONAL VARIATIONS IN WASTE HEAT

The variations in waste heat generation during the year are primarily related to variations in power demand or consumption. Owing to the climatic conditions in Alaska, the power consumption curve has only one peak which corresponds to the winter heating demand. Curves reflecting the seasonal variations in power consumption for the two major electric companies of Alaska are shown in Fig. 3.

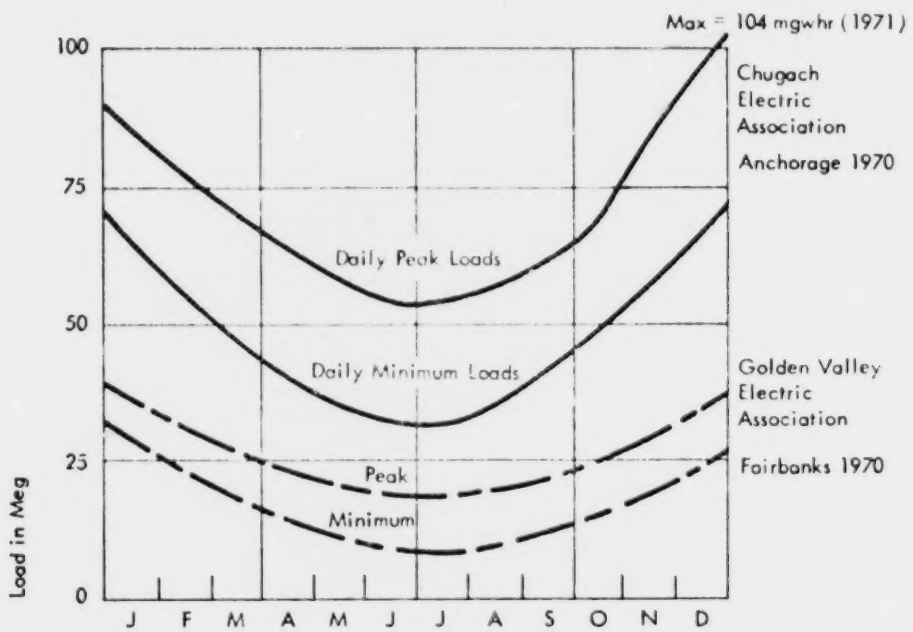

Fig. 3. Seasonal Variations in Alaskan Power Consumption

SEASONAL TEMPERATURE VARIATIONS FOR MAJOR CITIES

In order to establish the ranges of seasonal temperatures which might be encountered in Alaska, the four major cities were examined in detail. Mean temperature values have been determined for these annual conditions and for the extremes. These mean temperatures (in degrees Centigrade) are:

CITY	JANUARY		JULY		ANNUAL
	MIN.	MAX.	MIN.	MAX.	
Anchorage	-15	5.6		10	19.4 - 4.4
Fairbanks	-26	-18	8.9	22	-5 - 3.9
Ketchikan	-2.2	3.33	11.1	18	7.2 - 10
Juneau	-4.44	-1.11	10	18	4.4 - 7.2

OTHER COLD WEATHER REGIONS

A list of larger cities (100,000 or more population) with average January temperatures of less than 30 is given in Appendix A. An examination of statistics for steam-driven electric power generating plants[57,58] revealed that about 30% of all such plants are located in the cold climate areas as defined above and that these plants represent about one quarter of the total generating capacity in the continental United States. These plants would reject about 1.3×10^{15} BTU per year of waste heat in the form of heated water. The use of this heated water from steam power plants appears to have great potential for use in cold weather regions.

The future for the availability of discharged cooling water can be based on future demands for electric power. Steam power plant additions now being planned[57] amount to over 75% of the capacity currently installed. Specifically, of 51 very large generating units to be built in the next 5 years, over half are for cold weather areas and such areas will then have about one-third of the total generating capacity.

SECTION VII

POWER PLANT ADAPTABILITY

It appears that the majority of usable waste heat available results from the generation of electric power. For this reason a careful examination of power plant technology is important in order to identify present methods of waste heat disposal and the adaptability of power plants for optimizing the supply of waste heat to wastewater treatment processes.

Present circumstances for power plants vary with the local area concerned. Where sufficient quantities of water are available, once-through cooling is used and usually thermal discharges are not a problem. In other areas, once-through cooling is used, but is no longer acceptable and other means of handling the waste heat will be required. The problems of thermal discharges have been faced in some areas by the use of cooling ponds or cooling towers.

The two main areas to be considered in this section are the examination of the grouped utility concept and the identification of the limits of adaptability of power plants.

THE GROUPED UTILITY CONCEPT

The grouped utility concept has been presented for other applications in the past and can be defined as the locating and designing of two or more utilities so that they can take advantage of each other's contributions and requirements. In particular, the grouped utility concept has been considered for use with power plants in which the combination of electric power generation and seawater desalting at the same location is considered. For this study, the combination of interest is electric power generation and wastewater treatment.

Utility designs have generally not recognized any interdependence of electric power plants and wastewater treatment plants. Power demands for the future will have to be met by new power plants. The opportunity exists to design future plants to obtain maximum benefits from power generating systems. One possible design would be a combined power/wastewater treatment plant wherein some of the heat rejected from the power generation is utilized to improve efficiency in wastewater treatment. This combined system has the advantage of extracting some benefit from the waste heat before it is discharged to the environment.

Two general types of relationships can be identified when the utilities are combined. The simplest is where one-directional dependency is exhibited. For example, the power plant benefits the wastewater treatment plant but normally operates independently. The second type of relationship is mutual synergism, wherein each utility derives significant benefit from the other. This could be true if the power plant experienced lower costs due to the elimination of the necessity for cooling ponds or cooling towers. It must be understood that such waste heat utilization does not eliminate the heat, but merely transfers it from one place to another. The total heat load on the receiving water may still be the same, except for whatever heat would be lost to the atmosphere while the heated wastewater passed through the treatment plant.

Besides the benefits associated with waste heat, a grouped utility system might have other valuable outputs such as low cost, off-peak electrical power, off-peak mechanical power, off-peak steam, spent radioactive fuel elements, or perhaps low level radioactive wastes. In considering sequential use of resource energy and materials, it may be advantageous to consider a grouped utility system with more than two members to maximize total benefits from the combination. The inclusion of other appropriate industrial operations into the combine would depend on the local conditions and resources available.

LIMITS OF ADAPTABILITY OF POWER PLANTS

The location and operation of power plants is controlled by a number of factors which must be considered. Owing to the increased awareness of the environmental impact of industrial and municipal operations, it is becoming more and more difficult to find sites for power plants which satisfy all of the existing and developing criteria. This must also be taken into account for a grouped utility system which includes a power plant.

Power plant design includes operation under specified conditions in order to achieve economic production of electric energy. Certain operating parameters are particularly sensitive with respect to power costs and some of these parameters are directly related to waste heat usage. The two most important factors are the turbine exhaust pressure and condenser operating conditions.

The turbine exhaust pressure is purposely kept at a very low value to maximize the amount of work extracted from the steam in making electricity. Any increase in this pressure drastically reduces efficiency and increases costs. Turbine exhaust pressures for large new power plants range from 1.5 to 3.5 in. of mercury.[53] For this range of conditions the exhaust steam temperatures are from 33 to 50 C. This range corresponds to the maximum temperatures of steam entering the condenser. The condenser is actually a heat exchanger wherein the plant cooling water is used to condense the turbine exhaust steam. As with any heat exchanger, the design and operating conditions limit the closeness with which the cooling fluid approaches the hot fluid temperature. Standard practice[150] places the terminal temperature difference for typical condensers at about 5 C. The cooling water exit temperature will, therefore, be no higher than 28 to 43 C.

Other limitations concerning power plants are the seasonal variations in demand and the daily variations in demand. These demand fluctuations must be recognized since they control the output of waste heat available for use.

SECTION VIII

HEAT TRANSFER MECHANISMS

Having established the availability of waste heat in several forms, it is now important to identify methods of transferring this heat into typical wastewater treatment processes. Considerations of heat transfer mechanisms must include the basic methods, the actual equipment to be used, and the potential transfer efficiencies which can be achieved. Each of these areas will be delineated in the following paragraphs.

Whereas the majority of waste heat available is in the form of heated water discharges, hot exhaust gas is also significant for certain industries and locations. For this reason, these considerations will include heat transfer from gases as well as liquids.

HEAT TRANSFER METHODS

The overall problem of heat transfer can be broken down into two phases. The first phase is transfer of heat from the generation source to the point of use, and the second phase is transfer of heat into the appropriate process. Wherever a grouped utility system is established, the first phase of transfer would be essentially trivial or even non-existent. For current situations, however, this phase becomes very important and must be carefully examined to define areas of limitation.

The various heat transfer methods of interest are direct transport, direct contact, and indirect contact. In direct transport the heat is transferred by means of the hot fluid physically moving from one place to another. This covers, for example, the hot cooling water flowing in a pipeline from the power plant to the wastewater treatment plant. Such transfers normally involve negligible losses of heat, but under conditions of very long pipelines and/or very cold ambient air temperatures, significant heat losses may occur. In direct contact the heat is transferred from one fluid to another by direct physical contact between fluids. This covers, for example, hot water mixing directly with wastewater to be treated, or hot exhaust gases bubbling up through such wastewater.* In indirect contact the heat is transferred from one fluid to another with the fluids being separated by an appropriate physical barrier. An example of this would be the warming of wastewater by hot cooling water in a shell and tube heat exchanger.

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*In such direct application methods, contaminants in the waste stream must be carefully examined and considered since some contaminants are detrimental to certain wastewater treatment processes.

HEAT TRANSFER EQUIPMENT

For direct transport heat transfer, liquids and gases can conveniently be transported by means of pipelines appropriately sized. An alternative for liquid transfer would be the use of an open channel for flow, but it is recognized that this method greatly increases the associated heat losses to the atmosphere. Pipelines are usually buried underground and can be insulated to further reduce heat losses.

Direct contact transfer equipment can also consist simply of pipelines to direct the fluids to the point of use. In utilizing hot gases the piping should inject the gases well below the liquid surface to maximize contact time.* Properly designed diffusers must be used to achieve appropriate flow rates and gas bubble sizes. Two approaches can be considered for use of heated water. Either the hot water may be permitted to flow directly into wastewater to be treated (in which case a dilution occurs at the point of treatment) or the hot water could (after pretreatment) form all or part of the incoming water supply for the community being served (this latter method avoids dilution, but could result in considerably greater heat losses since this water flows throughout the entire water system).

Indirect contact transfer equipment could include the full range of heat exchangers currently used such as rotating disc, double-pipe, plate and frame, shell and tube, and plate heat exchangers. The two basic types consist of the confinement of one or both fluids. Examples of where only one fluid is confined are:

1. Heater coils immersed in a wastewater treatment tank with heated cooling water or hot exhaust gases circulating through the coils and the wastewater circulating by natural or forced convection;

2. The use of a cooling tower or trickling filter type device in which wastewater trickles down through a packing media and hot exhaust gases flow up the packing. (This could also be considered a variation of the direct contact type heat transfer.)

Examples of the system where both fluids are confined include all the arrangements of pipes, tubes, plates, and vessels in heat exchanger types indicated above.

Another unusual heating method should be mentioned although it does not strictly originate by using waste heat. A trickling filter operating in a sewage treatment plant in Nora Springs, Iowa[155] uses a translucent

*The use of hot gases may present problems owing to contaminants (such as SO_2) in the gas stream.

roof which allows radiant energy from the sun to warm the filter on cold days. The concept of using a cover over trickling filters or other wastewater treatment processes may have value if the space over the process can be beneficially heated by use of hot exhaust gases.

HEAT LOSSES AND TRANSFER EFFICIENCIES

Heat losses associated with direct transport of heated water in pipelines have been considered in detail for a wide range of conditions. Underground pipelines were examined for a variety of temperatures to determine heat losses by conduction to the surrounding soil and air. Equations were derived by starting with assumptions by Alter[4] using simple cylindrical geometry of insulating soil, and including the effect of a coefficient affecting heat transfer between the flowing water and the pipe wall. Ultimately it was possible to calculate heat losses in terms of the temperature drop experienced by the heated water for various pipeline lengths, depths of pipeline burial, flow rates, water temperatures, and ambient air temperatures (see Appendix D for equations and sample calculations).

Calculations were made for a basic case involving the flow of 1 MGD through a 4-in. diameter pipeline buried 6 ft below the surface. Similar results would apply for above-ground, insulated pipelines or insulated pipelines in channels. All of these methods are used in practice. The initial conditions called for a water temperature of 15 C and an air temperature of 5 C. The drop in temperature for the transported warm water is given below for a wide variety of important conditions:

Pipeline Length (miles)	VARIATIONS IN BURIAL DEPTH			VARIATIONS IN FLOW RATE THROUGH PIPE			
	Basic Case 6 ft Deep	4 ft	8 ft	Basic Case 1 MGD	0.1 MGD	0.5 MGD	2 MGD
1	0.2	0.2	0.2	0.2	1.2	0.3	0.1
5	0.9	1.0	0.8	0.9	4.6	1.4	0.5
10	1.7	2.0	1.6	1.7	7.1	2.6	0.9

Pipeline Length (miles)	VARIATIONS IN TRANSPORTED WATER TEMP.			VARIATIONS IN AMBIENT AIR TEMPERATURE		
	Basic Case 15 C	30 C	60 C	Basic Case 5 C	-5 C	-20 C
1	0.2	0.5	1.0	0.2	0.4	0.6
5	0.9	2.2	5.0	0.9	1.8	3.1
10	1.7	4.3	17.3	1.7	3.4	6.0

Heat transfer efficiencies for heat exchangers are best expressed by the overall heat transfer coefficients applicable for the various types of exchangers. Such coefficients are expressed in BTU/(hr)(C)(sq ft). It can be seen that in comparing heat exchangers with equal heat transfer areas, units with the largest coefficients are most efficient. The most efficient units tend to be the shell and tube and the plate heat exchangers. It appears that for the specific problems of waste heat utilization, the plate heat exchanger[163] can provide the greatest coefficients and the highest efficiencies of heat transfer. For plate heat exchangers, it is possible to use values of 1-2 C for the exchanger temperature approach (the water to be heated leaves the heat exchanger at a temperature 1-2 C below the inlet temperature of the warmer water). If fouling or scaling problems with these heat exchangers become difficult or expensive, other heat transfer methods such as rotating disc and cooling tower or trickling filter heat exchangers may be more appropriate.

POTENTIAL PROBLEMS WITH COATING/SCALING OF HEAT TRANSFER SURFACES

The efficiency of heat exchangers for indirect contact heat transfer depends partially on the maintenance of clean heat transfer surfaces within the equipment. Wastewater will be passing through one side of the heat exchanger and if any coating or scaling occurs in the passages, heat transfer efficiency will be adversely affected. Careful consideration must be given to the heat exchange method selected and the type of wastewater which is to be heated so that harmful levels of suspended solids and/or dissolved materials can be avoided. It is possible that pretreatment of the wastewater will be necessary no matter what type of heat transfer mechanism is utilized. Shell and tube and plate heat exchangers would be more subject to plugging, as well as more difficult to clean, than rotating disc and cooling tower or trickling filter heat exchangers.

Problems with scaling or fouling can occur with inorganic salts or organic materials. The particular problems will depend on the nature of the wastewater involved. Raising the wastewater temperature can cause a lower solubility for certain salts which could result in scale formation. Such scale can be avoided by use of chemical additives or the scale can be removed by acid cleaning. Both of these methods are very inexpensive. However, such scale formation is not likely for the small temperature increases involved. Fouling with organic material is, however, quite likely to occur unless proper precautions are taken.

Very little information is available concerning fouling and costs to prevent fouling. It should be pointed out that if such costs become significant, they could have an impact on the overall cost/benefit analysis of this study.

SECTION IX

TEMPERATURE DEPENDENCY OF UNIT PROCESSES AND ESTABLISHMENT OF REALISTIC TEMPERATURE RANGES

The modifications of Phases II and III towards placing a greater emphasis on economics restricted the work on temperature dependency to a few select ancillary processes. The temperature/efficiency model for the biological system (activated sludge) will be presented in Section X.

In order to establish definitive temperature ranges and to fill in the real world data gaps for the operation of activated sludge and ancillary systems, actual treatment plant performance data were compiled. An informational data sheet was sent to U.S. cities with a population of approximately 100,000 or more and average January air temperatures of 30 F or less. Appendix A contains a list of the cities contacted and a copy of the data sheet. Of the 65 cities contacted, 19 (or 29%) have responded with data on their processes. Of these, 10 (56%) contained data on activated sludge, and 9 (47%) showed operational data on other biological systems.

The operational data consisted partially of air and unit process temperature, flow rates, loading rates and effluent quality in terms of the 5-day BOD (Biochemical Oxygen Demand). From these data, operation of processes such as sedimentation and activated sludge could be evaluated to discern what effect various temperature ranges have on the effectiveness of treatment of these and other ancillary processes.

It is known that temperature differences will affect the rate of settling of particles in liquids by causing changes in the viscosity of the liquid and changes in density of both the particle and liquid (see Fig. 4). Data from various papers[129,135] also indicate that as temperature is increased, the velocity at which particles will settle is also increased (see Fig. 5). In observing wastewater treatment plants, Ridenour[135] found that greater efficiencies were obtained from the sedimentation tanks in summer than in winter. The cause of this increased efficiency in these cases has been attributed to the higher temperature of the sewage in the summer.

Plots of data were made of temperature vs percent removal of suspended solids. A comparison of temperature data as found in the literature, derived from bench scale models (Fig. 6) and actual data received from treatment plants (Fig. 7), was made to determine what correlation (if any) for removal efficiencies can be made with the physical/chemical changes such as density, viscosity, solubility and reaction rates.

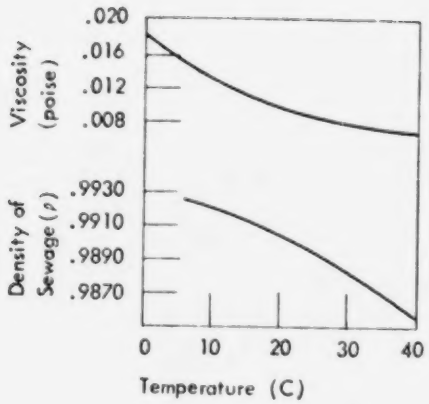


Fig. 4. Fluid Properties as Affected by Temperature

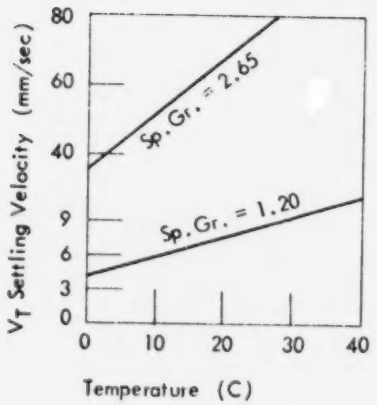


Fig. 5. Settling Velocity as Affected by Temperature

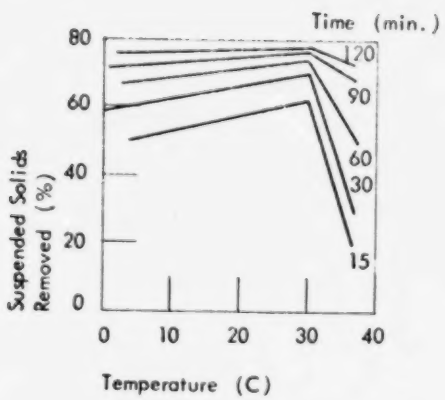


Fig. 6. Temperature and Detention Effects on Removal of Suspended Solids

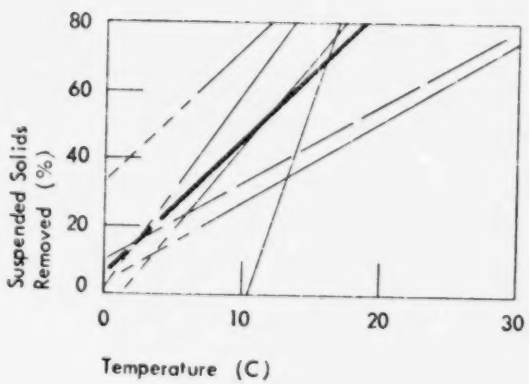


Fig. 7. Field Data Plot of Effect of Temperature on Removal of Suspended Solids

Figure 6 indicates that detention time is a factor in the overall removal efficiency of the primary sedimentation process. It becomes apparent that even at the lower detention times (15 to 60 min), high quality effluent can be achieved if wastewater temperatures are raised significantly. The implication is that greater removal of suspended solids is possible and this beneficial effect can be utilized in two ways: (1) existing units could be operated at shorter detention times and still retain good removal efficiencies; (2) new units could be designed with smaller capacities to achieve the same performance. The data plotted in Figs. 6 and 7 also indicate that an optimum temperature range for primary sedimentation lies between 10 and 20 C for average detention time employed by wastewater treatment plants.

From the data plotted in Fig. 7, there is an indication of a greater removal of suspended solids with the increase of sewage temperature. The removal of suspended solids for sewage at average normal temperatures (10 C or 50 F) is between 35 and 65%. The established curve indicated by a heavy dark line in Fig. 7 shows a removal of 45% for this temperature, indicating a curve with a good fit. The removal is expressed by an incremental increase of 20% removal of suspended solids per each 5 C rise in temperature. This increase is only relevant as long as the "normal" range of detention periods (45-120 min) is maintained.

The most common measure of efficiency in treatment plants is related to the amount of BOD removal. For a primary sedimentation basin operating at average sewage temperatures (10 C), a removal range of 20 to 40% BOD is possible.[20] The field data plotted in Figs. 7 and 8 show a 35% BOD removal also at the average sewage temperature. This value lies within the 20 to 40% range indicating a curve with a good fit.

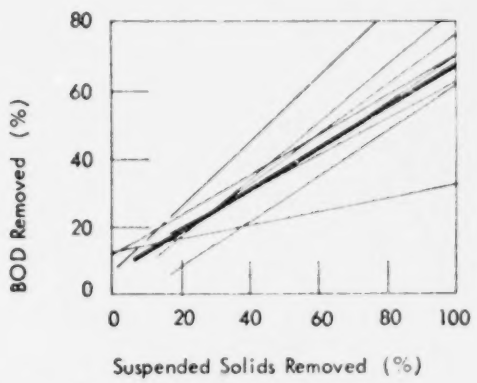


Fig. 8. Field Data Plot of Suspended Solids vs BOD Removal

Table 4 indicates that if temperatures of the sedimentation basin could be maintained at 2.5 C above normal sewage temperature, the upper limit of normal removal efficiency of BOD (40%) would be attained. With an increase of 10 C, the removal of BOD could be increased by 15% above the upper limits of the BOD removal range. Since the overall efficiency of biological processes is linked with pre- and final sedimentation, the increase of the pre-sedimentation unit would have an impact on the total treatment system.

Table 4

EFFECT OF TEMPERATURE
CHANGES ON BOD REMOVAL

TEMPERATURE (Centigrade)	SUSPENDED SOLIDS (% Removed)	BOD (% Removed)
10	45	35
12.5	55	40*
15	65	45
17.5	75	53
20	85	55

*Upper limit, normal removal.

SECONDARY CLARIFICATION

One of the basic features of sewage treatment processes involving high rate activated sludge is secondary clarification (the separating and the recycling of solids). Eckenfelder and O'Connor[50] describe the activated sludge particle as a "miscellaneous collection of microorganisms such as bacteria, yeasts, molds, protozoa, rotifiers, worms, and insect larvae in a gelatinous mass." Reed and Murphy[129] indicate that temperature can be a significant factor in the metabolic processes involved and could have an (indirect) influence on settling. The plot (Fig. 9) of Settling Velocity vs Temperature at various sludge concentrations indicates that:

1. The zone settling is limited by the upper limits of concentration MLSS

2. There is an ultimate temperature dependent settling velocity at the lower concentration of MLSS.

Final sedimentation of activated sludge is characterized by zone settling. The floc particles adhere together and the mass settles as a blanket forming a distinct interface between floc and supernatant. The sludge is a function of the biokinetics of the system and therefore its settling behavior is strongly dependent on microbial characteristics and operational parameters. At a temperature increase of 10°C above the 10°C base temperature, and low loading rates at 2000-3000 mg/1 MLSS (see Fig. 9), the settling rates are increased by an average of 25 percent. At a temperature of 20 C and low loading rates as 2000 to 3000 mg/1 MLSS, the settling rates are increased by an average of 26%.

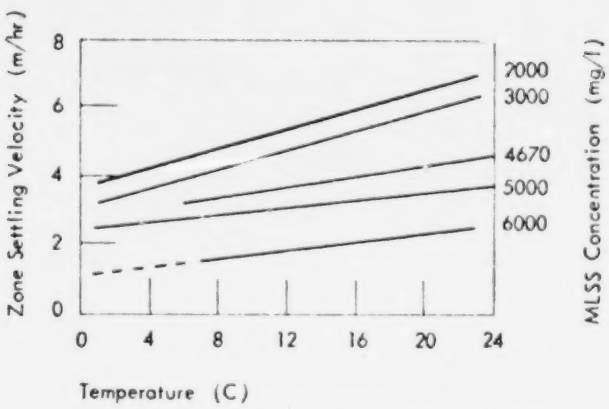


Fig. 9. Temperature Effect on Zone Settling

Organic loading and initial solids concentration are important parameters of design as indicated by the work of Ford and Eckenfelder and Dick and Ewing. The effect of temperature on activated sludge settling is inconclusive. Several investigators have observed the same velocity-viscosity relationships as predicted by Stokes' Law. Others note that temperature differential did not appear to have any significant effect.

The work of Reed and Murphy[129] is summarized in Fig. 9. It is evident that the influence of temperature on settling velocity decreases as the initial solids concentration increases. It should be noted that the F/M was 0.03 on a BOD_5 basis and therefore the unit was operating under extended aeration conditions. A dispersed floc is predominant at such low loadings and hence more sensitive to temperature variation.

TEMPERATURE EFFECTS ON OXYGEN UTILIZATION

It is apparent that temperature influences the rate of chemical and biochemical reactions. It can be shown that in the ranges of optimum biological activity, a two- to three-fold increase in reaction velocity is experienced for each 10 C rise in temperature.[22] Since oxygen utilization represents a sequence of related reactions (oxygen transfer, adsorption, oxidation, etc.), it is probable that temperature effects are not the controlling factor under all temperature conditions.

In most activated sludge treatment plants air is supplied in excess so as to ensure an adequate supply of oxygen required for biological metabolism and a high level of mixing. It is doubtful, therefore, that an increase of temperature would cause any change in oxygen utilization with this existing operation of supplying excess air.

EFFECTS OF TEMPERATURE ON NITRIFICATION

One of the prime nutrients which contributes to the eutrophication of surface waters is nitrogen in the fixed forms of ammonium and nitrate ions. Many states are now requiring that Nitrogen Oxygen Demand (NOD) be considered as part of the analysis performed to ascertain the total pollutional impact on these surface waters.

Nitrogen may be present in a wastewater as organic nitrogen, ammonia nitrogen, and nitrite and nitrate nitrogen. During the course of biological treatment, organic nitrogen is broken down to ammonia and, depending on the process conditions, ammonia may be progressively oxidized to nitrite and nitrate. Some organic nitrogen forms are refractory and pass through the process. During the BOD removal phase of the process nitrogen is assimilated into bacterial protoplasm. A portion of this nitrogen is released back to solution through the endogenous metabolism of the biomass. Nitrites and nitrates are biologically reduced to nitrogen gas under appropriate conditions. It is usual that conventional activated sludge and trickling filter processes remove 20 to 40% of the total nitrogen.[158]

The effects of temperature on nitrification in the activated sludge process is not well documented; however, in laboratory studies conducted by Ludzack et al[103] it was observed that nitrification was not significant at 5 C. Another effect on the nitrification process can be seen in Fig. 10, which represents the work done by Borchardt.[18] This figure indicates that the rate of nitrification increases with the increase of temperature up to a maximum of 30 C. If the only consideration is the effect of temperature, with adverse winter conditions imposed (5-10 C), the detention time that would be required to obtain complete nitrification would be about five times as great as for temperatures in the 20-30 C range. This can be seen in Fig. 11.

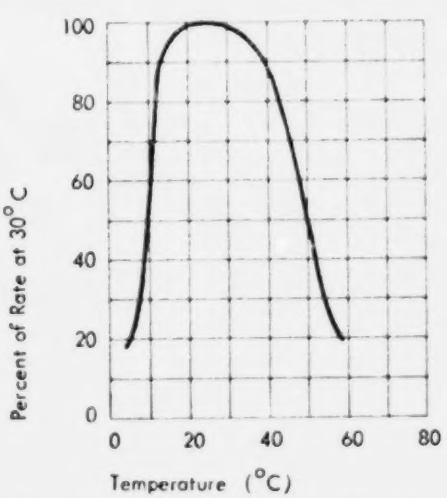


Fig. 10. Temperature Effect on Rate of Nitrification

It should be clearly understood that the low range temperature effects could be overcome by the adjustment of the mixed liquor suspended solids (MLSS), pH and aeration tank capacity.

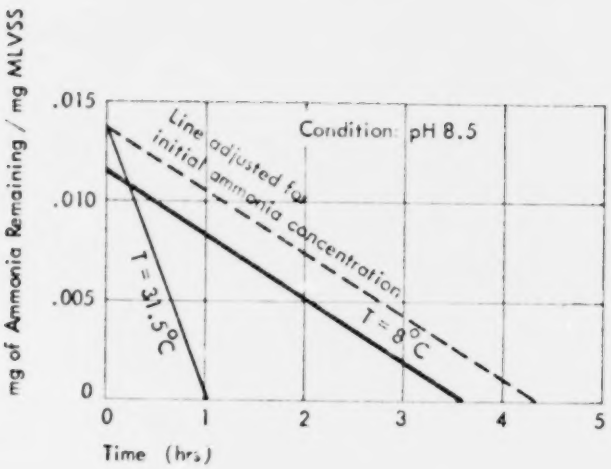


Fig. 11. Effect of Variation in Temperature (Journal WPCF, Sept. 1971)

Table 5 indicates the effect of increased temperatures on some of the nitrification parameters. A sample calculation appears in Appendix D of this report. The table also indicates that sludge age is highly temperature dependent.

Consider an existing wastewater treatment plant operating within low temperature range. Nitrification could still be carried out in the same aeration tanks as carbonaceous removal providing that adequate sludge age, aeration volume, hydraulic detention and sufficient oxygen are supplied. To obtain the required parameters for nitrification without changing most of the plant's existing parameters, and possibly without physically changing the capacity of the aeration tanks, the temperature could be elevated by the utilization of waste heat. This would require additional study to better define the rate constants of nitrification which takes place during the latter stages of carbonaceous oxidation.

Table 5

TEMPERATURE EFFECTS ON NITRIFICATION PARAMETERS

TEMPERATURE (C)	SLUDGE AGE (DAYS)	REQUIRED AERATION VOLUME ($FT^3 \times 10^4$)	HYDRAULIC DETENTION TIME (HR)	OXYGEN REQUIREMENT IN ADDITION TO CARBONACEOUS OXIDATION (LB/DAY)
10	10.5	7.67	4.6	1740
15	5.3	5.82	3.5	1530
20	3.5	4.07	2.44	1388

TEMPERATURE EFFECTS ON DISINFECTION

Disinfection is a term applied to those processes in which pathogenic microorganisms, t[illegible] their spores, are destroyed.

Chlorine and chlorine compounds are the main disinfection agents used in the United States for the treatment of municipal water supplies and wastewater due to the specific high toxicity of chlorine for microorganisms responsible for water-borne diseases.

The primary factors which govern the bacterial efficiency of both free and combined available chlorine are based on the temperature of the water in which the contact is made (the higher the temperature, the more effective the di[illegible]), and the time of contact of organisms and bacterial agent [illegible]er time, the more effective the disinfection).

The temperature effect on the rate of reaction can be expressed by the general Arrhenius equation:

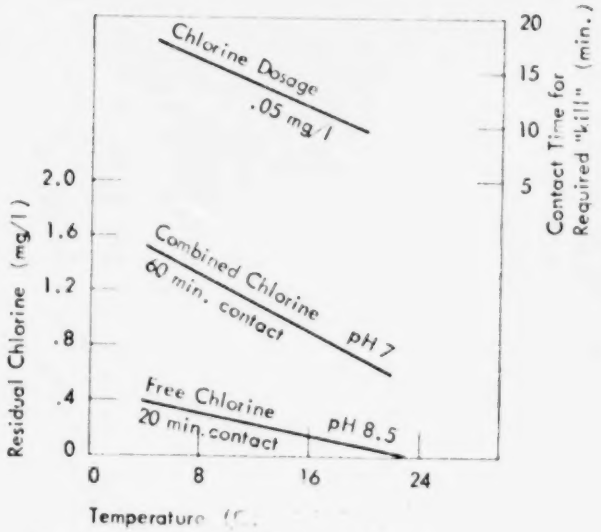


Fig. 12. Temperature Effect on Chlorination Process

$$\log t_1/t_2 = \frac{\Delta H_a (T_2-T_1)}{2.3\ R\ T_1T_2} \qquad (1)$$

where t_1 and t_2 are times required for equal percentage kill at temperatures T_1 and T_2 and at the same concentration of disinfectant.

H_a = absolute energy needed for a given chemical compound (e.g., free of combined chlorine at a given pH)

R = universal gas constant

T = absolute temperatures

Figure 12 shows the relationship of combined and free available chlorine and contact time of elevated temperatures. There are two possible

benefits that can be realized from operation at optimum temperature ranges (15-20 C). For a given detention time and pH the amounts of residual chlorine needed are reduced by 20 to 40%, hence the applied dosage for combined and free chlorine is also reduced 20 to 40%. In addition, if the dosage is held constant, then the contact time required to obtain the needed "kill" is also reduced 20 to 40% with increased temperature. This would allow for construction of smaller contact chambers with a reduced capital expenditure for the chlorination chamber.

TEMPERATURE EFFECTS ON VACUUM FILTRATION

Sludge variables which affect the dewatering process of vacuum filtration are liquid (filtrate) viscosity, solids concentration, and specific resistance. For a given sludge of a given temperature, filtrate viscosity is fixed. Solids concentration and specific resistance will vary, however, and are dependent upon sludge conditioning prior to filtration.

If the filter yield is represented by

$$B(\text{yield}) = \left(\frac{2\ \Delta p\ w}{u\ R'\ tc}\right)^{1/2} \qquad (2)$$

where Δp = drum filter vacuum in in. of mercury

w = fraction of cycle time

u = liquid viscosity, lb mass/ft sec

tc = time for one filter cycle, sec

R' = specific resistance, sec^2/lb mass

V = volume of filtrate, ft^3

B = filter yield, lb force/ft^2 sec

S = area of filter, cake-ft^2

and area of filter surface

$$S\ (\text{area}) = \frac{Vw/tc}{B} \qquad (3)$$

With u the viscosity being temperature dependent, a rise in temperature produces an increase in the filter yield. This in turn reduces the drying area needed by the filter. The effect of filter yield and area with changes in temperature are shown in Table 6.

Table 6

TEMPERATURE EFFECTS ON FILTER YIELD AND AREA

TEMPERATURE (centigrade)	FILTER YIELD (B) (lbs force/ft^2, S) (10^{-5})	AREA REQUIRED (sq ft) (10^2)	REDUCTION OF AREA (%)
5	4.65	3.06	
10	4.85	2.93	Normal sewage temperature
15	5.28	2.70	8
20	5.50	2.59	11.6
25	5.62	2.54	13.3

While the percent reduction in area is not dramatic, the treatability of the sludge (i.e., the increase in filter yield) becomes an important factor, especially in cold climates. With an increase in filter yield the performance of existing filters would produce an increase of filter cake (lb) per unit area and time. For example, if a plant operating a vacuum filter at average sewage temperature were to increase the temperature of the sludge applied by 10 C, there would be a 12% increase of filter yield area for a given operating time, decreasing the power cost of operating the filter unit. In addition, the elevated temperature of the filter cake could reduce the operating cost of an incineration process by reducing the heat requirement to incinerate the cake.

SECTION X

TEMPERATURE EFFECTS ON ACTIVATED SLUDGE

The effects of temperature on the activated sludge process have received little attention in the past because of the lack of an economical method for changing or controlling wastewater temperatures.[61] With larger quantities of waste heat being discharged from various power generation sources and industrial complexes and improved methods for heat exchange and transfer, it may now be possible to improve the efficiency, and therefore the economic operation, of secondary treatment systems. This improvement due to the utilization of waste heat would be most beneficial in areas which are being newly developed (for optimum location of treatment facilities to waste heat discharge) and in those areas with prolonged cold seasons.

There are many variables which affect the performance and efficiency of the activated sludge process. Some of these are organic loading, temperature, type of substrate, and organism growth pattern. Activated sludge, being a biological process, should have a definite temperature range at which organism growth patterns become optimum. Changes in the growth pattern could affect the competitive position of a species and their relative distribution in a population. This change in population (either increasing or decreasing) due to the temperature would affect the oxygen utilization and the synthesization of organic matter with a definite effect on performance.

The growth of cells and removal of BOD (as affected by temperature) approximately doubles for each 10 C. As the temperature is increased more substrate organic material is required to synthesize 1 gram of solids; in other words, increased utilization of organic matter (BOD) takes place. This is shown in the plot of Fig. 13.

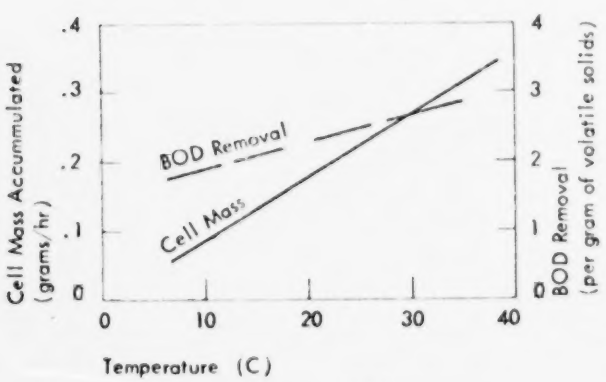


Fig. 13. Temperature Effects on Biological Properties

It has been found that temperature effects on biological waste treatment processes due to variations in liquid temperature occur in two specific and interdependent ways. The first effect concerns the oxygen utilization rate, which

reflects the energy transfer of the process. This has a defined temperature relationship which is expressed by a temperature coefficient. The second effect concerns the relationship that exists between the oxygen transfer rate to the biomass and the oxygen utilization rate of the biomass.

The temperature effect on the performance of a particular process is usually expressed by a modification of a process rate constant and is an adaptation of the Van't Hoff-Arrhenius equation:

$$K_T = K_{20\ C}^{\theta(T-20)} \qquad (4)$$

where K_T = rate constant (day^{-1}) at temperature T

K_{20} = rate constant (day^{-1}) at 20 C

θ = temperature coefficient

The determination of θ and K may be accomplished in several ways. For example, a semilog plot of percent BOD remaining vs detention time will yield a slope representative of the reaction rate K; then, a plot of K vs temperature (as shown in Fig. 14) will yield the coefficient θ. Values for the reaction rates may also be obtained by direct calculation by using Eq. (5) for a complete-mixed aeration system:

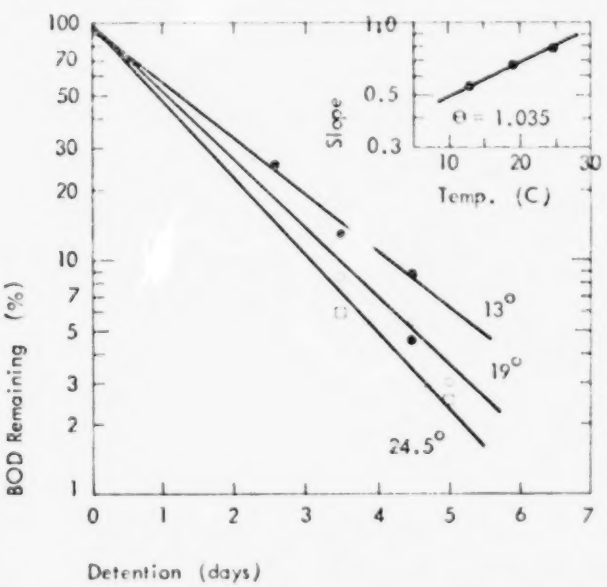


Fig. 14. Derivation of Temperature Coefficient

$$\frac{So - Se}{Se} = KX_v t \qquad (5)$$

where So = influent BOD

Se = effluent BOD

X_v = aeration volatile solids concentration

t = aeration time

K = mean reaction rate coefficient

One of the most responsive factors relating temperature effect to process performance is the food-microorganism ratio, F/M.[49] The biomass is dispersed at very high values of F/M. At intermediate organic loading levels, dispersed filamentous growths may develop. At low loading levels, flocculation occurs, resulting in the formation of gelatinous flocs containing millions of individual organisms.

Table 7 shows temperature effects on the activated sludge process. BOD removal and oxidation is affected by changes in growth patterns. The amount of oxidation depends on diffusion of oxygen into the biological floc. At conventional mixing intensities, relatively large flocs are generated and at low temperatures a low oxygen utilization rate permits diffusion of oxygen to a greater depth in the floc and, therefore, a large portion of the floc is aerobic. At high temperatures, the increased respiration rate causes more rapid depletion of the oxygen and only a small portion of the floc is aerobic. At high mixing intensities, such as found in an aeration basin, the smaller floc sizes may be fully aerobic under all temperature conditions and the coefficient θ will increase. At the higher F/M ratios, the dispersed filamentous growths will exhibit a high temperature dependency.[50]

Table 7

TEMPERATURE EFFECTS ON THE ACTIVATED SLUDGE PROCESS

TEMPERATURE RANGE (°C)	F/M***	MLVSS (mg/l)	S_o (mg/l)	SUBSTRATE	BATCH OR CONTINUOUS	DETENTION TIME (hr)	θ
4 - 45	0.58	1,600**	623	Synthetic sewage (dry dog food meal)	Batch (bench scale)	16.00	1.035
5 - 30	0.44	1,100	435	Slurried dog food meal	Continuous (bench scale)	12.00	1.037
	0.81	1,100	435	Dog food meal with dextrose and gelatin			1.041
	0.45	1,870	750	Phenol			1.016
26 - 37	0.57	3,200**	229	Kraft black liquor	Continuous (bench scale)	3.00	1.006
9 - 17	2.03	480**	108	Domestic sewage	Continuous (pilot plant)	2.67	1.076
	0.43	2,640**	124				1.0
	0.22	4,800**	115				1.0
10 - 25	0.74	800**	248	Domestic sewage	Batch (bench scale)	10.00	1.015

* Ref. 49.

** Assumed MLVSS = 80 percent MLSS.

*** F/M = lb BOD_5/lb MLVSS day.

It is apparent that the effect of temperature on the activated sludge process is related both to the loading (F/M) level and to the intensity of mixing in the process.

A generalized approach will be taken in the development of the activated sludge model. It will be based on the premise that the objective of biological treatment is to remove oxygen-consuming organic matter from wastewater and reduce, oxidize, or stabilize it to some desired degree. The amount of this waste that is present or reduced is usually measured or reported as BOD. The approach utilized recognizes and makes use of the following factors:

- The BOD bottle test will equate differences in the various organic and inorganic oxygen consuming substances encountered so long as BOD continues to be used as the primary criteria for measuring performances and efficiencies of biological treatment systems.

- The BOD loading will determine the mode of activated sludge operation. It will establish removal efficiency, oxygen requirements, excess sludge production, etc.

It is now plausible to examine the effects of temperature upon biological oxidation processes of waste treatment by relating the reaction rate coefficient K to temperature in the form of Eq. (4), which is repeated here for reference:

$$K_T = K_{20}\, \theta^{(T-20)}$$

where K_T, appearing in Eq. 4, is used in

$$L = L_a\, 10^{-K_T t} \qquad (6)$$

It should be noted that in this form L (ultimate first stage BOD remaining at time t) or L_a (at t = 0) may be in any units, as long as they are consistent. In fact, both could be in terms of 5-day BOD, rather than first-stage BOD.

The fraction f of BOD remaining in the effluent after time t of the oxidation process, such as occurs in activated sludge, is given by

$$f = \frac{L}{L_a} = 10^{-K_T t} \tag{7}$$

combining Eqs. (4) and (7)

$$f = 10^{-tK_{20}\,\theta(T-20)} \tag{8}$$

Now letting P, the fraction removed, equal (1-f) yields:

$$P = 1-10^{-tK_{20}\,\theta(T-20)} \tag{9}$$

It is Eq. (9) which was incorporated into the computer model (Appendix C) to analyze the effects of temperature on the efficiencies of the activated sludge process in the reduction of 5-day BOD.

The computer output (shown in Table 8 and Fig. 15) indicates that the removal percentage increases with temperature increases. The enveiopes which are formed around each rate constant indicate the effect of the temperature coefficient on the removal efficiency. A decrease in θ produced increase in removal of 5 to 9% at the lower temperatures.

Table 8

COMPUTER OUTPUT
TEMPERATURE EFFECTS ON REMOVAL RATES

TEMPERATURE (C)	θ = 1.047			θ = 1.035		
	K=.25	K=.125	K=.0625	K=.25	K=.125	K=.0625
	Percent Removed			Percent Removed		
1	70	45	26	77.2	54.5	31
8	81	57	33	85.1	62	37.5
16	92	70	45	93	71.4	47
21	95	78	53	95	78	53
26	98	99.9	99	99	99.9	99

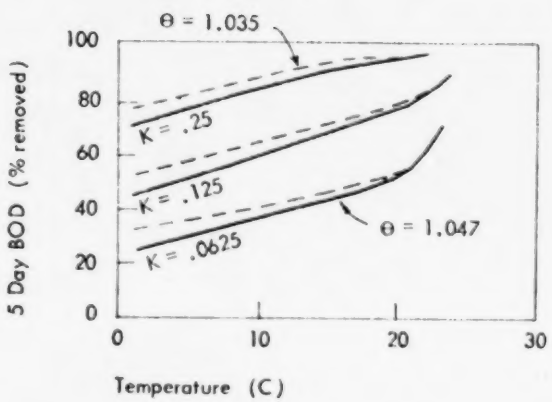
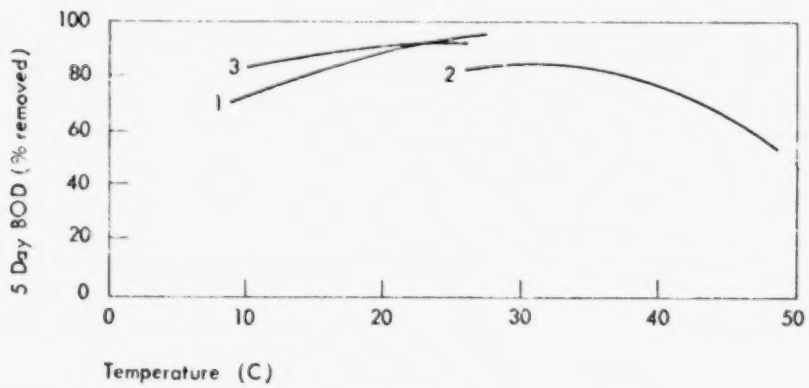


Fig. 15. Temperature Effects on Percentage BOD Removal

Plots of temperature effects on different wastes with various MLSS concentrations and aeration times are given in Fig. 16. This shows an increase of removal with increases in temperature up to 30 C. The largest increase, 22% removal, occured with Baker's yeast. Domestic sewage treated by activated sludge exhibited only a 6% increase in removal efficiency.



NOTE: 1. Culture Waste of Baker's Yeast
Aeration 8 hr, MLSS 3500-4000 ppm
Ref. 108

2. Simulated Kraft Effluent
Aeration 3 hr, MLSS 3400-4400 ppm
Ref. 26

3. Domestic Sewage
Aeration 6 hr, MLSS 850-1168 ppm
Ref. 116

Fig. 16. Temperature Effects on the BOD Removed by Activated Sludge

The temperature range for the most beneficial operation of the activated sludge process is from 15 to 30 C, with 26 C seeming to be optimum (Figs. 15 and 16). Although the ranges were based on limited data, it is apparent that higher efficiencies can be obtained with increases in temperatures.

SECTION XI

HEAT TRANSFER COSTS

The costs of achieving heat transfer from a waste heat source to a wastewater treatment process can be broken down into two basic elements. The first is the cost to transport the waste heat from the source to the location of the treatment plant. This cost is dependent on the distance between the source and the use point; it also varies with the amount of waste heat transported. The second cost element is that required to transfer heat from the treatment plant site into the actual process of interest.

Costs for waste treatment plants are usually expressed in cents/1000 gal treated. Costs for heat transfer will also be expressed in cents/1000 gal of wastewater treated. Heat transfer costs are those costs required to raise the wastewater temperature by a fixed amount. The standard temperature increase of greatest interest for this study is about 10 C, which corresponds to the average temperature increase expected from using electric power generation cooling water and the most efficient heat transfer methods. Other temperature increase regimes will be examined to determine the most attractive system from an overall economics viewpoint.

HEAT TRANSPORT COSTS

Costs have been calculated for transporting sufficient heated water to raise the wastewater temperature by 10 C in treatment plants with capacities from 1 to 100 MGD. Distances of from 1 to 25 miles between the power plant and the treatment plant have been considered.

The cost items involved include: capital costs for the pipeline and pumping system, operating and maintenance labor for this system, and electric power requirements for pumping. Capital costs have been converted to annual costs based on 4-1/2% for 25 years (typical value used in previous EPA studies).

For any particular pipeline length and flow capacity, costs for this system depend on the discharge pressure of the cooling water, the pressure at which this water must be delivered, and the difference in elevation between the power plant and the treatment plant. It is assumed that the water is available and delivered at ambient pressure (0 psig). Minimum costs occur where the treatment plant is downhill from the power plant and no pumping is required. The worst case considers that the treatment plant is 100 ft above the power plant in elevation.

Using the above assumptions, costs adjusted to 1971 for the heat transport portion have been calculated[124,125] and are presented below. Sample calculations for these figures are given in Appendix D to indicate the method of computation.

Table 9

HEAT TRANSPORT COSTS
(In cents/'000 gal*)

DISTANCE FROM POWER PLANT TO TREATMENT PLANT (miles)	CAPACITY OF TREATMENT PLANT (MGD)		
	1	10	100
1	3.7-7.3	1.5-3.9	1.3-2.8
5	8.9-13.6	2.9-5.4	2.3-3.8
25	35.0-44.9	9.5-12.7	7.0-9.1

*The range of cost values covers the cases from minimum cost (no pumping required) to maximum for this study (100 ft of elevation difference between plants).

The costs in Table 9 do not reflect any credit which may be due the system because of the elimination of the normal piping system used to transport the discharged cooling water to the nearest receiving water. This savings could be significant for certain power plants. Heat transport costs will be negligible in the case of an integrated complex where the power plant is located adjacent to the wastewater treatment plant.

HEAT TRANSFER COSTS

The costs associated with transferring heat into any treatment process depend on the amount of heat transferred and the method of heat transfer. The two basic heat transfer methods of interest are:

1. The direct method, whereby the hot water is added directly to the wastewater,* and

2. The indirect method, whereby the wastewater is heated by the hot water in a heat exchanger.

*For this method it must be remembered that contaminants in the hot water could be detrimental to certain wastewater treatment processes.

The direct method has the advantage of optimizing the total heat transfer, but a dilution of the wastewater occurs and larger volumes of water must be treated. The indirect method has the advantage of raising the wastewater temperature the most, but costs are higher.

The standard case assumed for this study is the one in which wastewater temperature is raised to 10 C, and there is a 1 C temperature approach for the heat exchanger. This requires use of the indirect heat transfer method with the highest efficiency heat exchangers. If the wastewater temperature is originally 10 C, then the standard case means raising it to 20 C. For this case, the original hot water temperature is 21 C as it enters the heat exchanger. Use of a plate heat exchanger would then yield an exit temperature of 16.8 C for the hot water stream. A heat balance for this standard case reveals that 2.4 gallons of hot water are required for every gallon of wastewater heated. This standard case gives the highest heat transfer costs. Lower costs can be achieved in two ways. Less efficient heat exchangers can be used which give reduced costs but lower temperatures for the wastewater. The second method of reducing costs is to use direct heat transfer. This gives greatly reduced costs, but lower temperatures result and larger volumes of wastewater must be treated.

The cost items involved include capital costs for the pumping, piping, and heat exchanger system, operating and maintenance labor for this system, and electric power requirements for pumping. Costs (adjusted to 1971) for the heat transfer portion using alternative methods have been calculated and are presented below.

Table 10

HEAT TRANSFER COSTS*
(In cents/1000 gal)

HEAT TRANSFER METHOD	CAPACITY OF TREATMENT PLANT (MGD)		
	1	10	100
Indirect: 10 C rise	2.4	1.2	1.1
Indirect: 8 C rise	2.0	1.0	0.9
Direct: 7 C rise**	0.63	0.34	0.28

*Without transport costs (if any).

**The wastewater volume is 3.4 times as great for this case as for the volume to be treated using indirect heating.

OVERALL HEAT TRANSFER COSTS

To obtain the overall costs, the transport and transfer costs are added together. It has been assumed that transport costs for the integrated complex are zero. Overall heat transfer costs for the parameters studied are presented in the following table.

DISTANCE FROM POWER PLANT TO TREATMENT PLANT (miles)	METHOD OF HEAT TRANSFER	TEMPERATURE RISES (C)	CAPACITY OF TREATMENT PLANT (MGD)		
			1	10	100
0	Indirect Transfer	10	2.4	1.2	1.1
	Indirect Transfer	8	2.0	1.0	0.9
	Direct Transfer	8	0.63	0.31	0.28
1	Indirect Transfer	10	6.1-9.7	2.7-5.1	2.4-3.9
	Indirect Transfer	8	5.7-9.3	2.5-1.9	2.2-3.7
	Direct Transfer	8	4.3-7.9	1.8-4.2	1.6-3.1
5	Indirect Transfer	10	11.3-16.0	4.1-6.6	3.4-4.9
	Indirect Transfer	8	10.9-15.6	3.9-6.4	3.2-4.7
	Direct	8	9.5-14.2	3.2-5.7	2.6-4.1
25	Indirect Transfer	10	37.4-47.3	10.7-13.9	8.1-10.2
	Indirect Transfer	8	37.0-46.9	10.5-13.7	7.9-10.0
	Direct Transfer	8	35.6-45.5	9.8-13.0	7.3-9.4

SECTION XII

HEAT TRANSFER BENEFITS

The benefits accruing to the various wastewater treatment processes should ultimately be expressed in terms of savings in cents/1000 gal treated. In these terms, the benefits may be compared with costs and the benefit/cost relationship for waste heat application may be evaluated. In general, the range of plant sizes from 1 to 100 MGD are explored. It should be indicated that the quantified benefits shown in this section are based solely on the temperature effects and not the increase in plant size.

There are two basic situations to be considered:

- The waste heat as applied to an existing plant
- The waste heat as applied in a new plant.

In a new plant, use of the waste heat can be incorporated directly into design considerations and the most efficient utilization of the heat will result. Incorporation of waste heat application into an existing plant requires the solution of special problems depending on whether direct or indirect heat transfer is employed. If the direct heat transfer method is used, there must be sufficient hydraulic capacity in the system to handle the additional water. In addition, a suitable point to add the hot water must be located where the combined waters will mix adequately to give a uniform temperature. If the indirect heat transfer method is used, a suitable point to divert wastewater from the main flow path must be located and sufficient area must exist for the heat exchanger equipment. In addition, the hot water pipeline must be situated within the existing equipment network to feed the heat exchanger and discharge to an appropriate receiving water.

Benefits for the new plant will generally appear as lower capital costs since it is possible for smaller treatment units to yield the desired effluent quality. Benefits for the existing plant cannot be so directly quantified since the usual result will be a higher quality effluent than that of a plant not utilizing waste heat. This latter case can be handled in two ways:

1. It can be assumed that the higher quality effluent will be mandatory in the future and the existing plant (without use of waste heat) would have to add processing equipment (with resultant costs) to meet this goal.

2. Instead of yielding a higher quality effluent, the use of waste heat could permit a higher flow rate through a process unit at the normal level of quality (in this way the waste heat use saves on added equipment for the case where higher flow rates become mandatory in the future).

Each of the treatment processes will be examined separately to determine the benefits on an individual basis. It appears that the optimum use of waste heat is to raise wastewater temperatures at the entrance to the treatment plant and yield the summation of benefits from each of the processes. Owing to the problems and costs involved with heat exchanger fouling, it may, however, be more advantageous to heat the wastewater at a point further downstream in the treatment plant (e.g., after primary treatment).

PRIMARY SEDIMENTATION

The data presented in Section IX show the effect of temperature on primary sedimentation. The information plotted in Fig. 6 shows variations in percent of suspended solids removed with temperature change for a wide range of detention times. This figure is used to determine the effects of using waste heat for primary sedimentation.

By means of the literature examination, the range of detention times from 45 to 120 minutes was investigated to find the effects of waste heat use in the following forms: (1) the reduced capacity permitted for new plants; and (2) the additional capacity required in existing plants if waste heat were not employed (this additional cost is saved in the case of waste heat use). The results of this investigation are given below:

Table 12

EFFECTS OF WASTE HEAT UTILIZATION ON PRIMARY SEDIMENTATION

	NEW PLANTS	EXISTING PLANTS
Capacity required without waste heat use	1.00	1.19-1.33
Capacity required with use of waste heat		
• Indirect heat transfer: 10 C rise	0.70-0.77	1.0
• Direct heat transfer: 7 C rise	2.7-3.0	3.2-3.6

It can be seen that the indirect heat transfer method is advantageous for new and existing plants. The direct heat transfer method is not beneficial in either case since the added volume in the system is not compensated for by reduced capacity requirements at elevated temperature. It must be remembered that the direct heat transfer case assumed was for hot water at a temperature 10 C above the wastewater temperature.

A more detailed study revealed that direct heat transfer only became beneficial over normal operation at hot water temperatures greater than 30 C above that of the wastewater.

The benefits of the indirect heat transfer method indicated above can be converted to cost figures by considering capital, operating, and maintenance costs for primary sedimentation.[65,143] The resultant savings to this process are given below:

Table 13

COST SAVINGS FOR PRIMARY SEDIMENTATION
(heat transfer costs excluded)

COST SAVINGS IN CENTS/1000 GAL	TREATMENT PLANT CAPACITY (MGD)		
	1	10	100
New Plants	0.18-0.23	0.19-0.25	0.19-0.24
Existing Plants	0.15-0.25	0.16-0.28	0.16-0.26

SECONDARY CLARIFICATION

The effects of temperature on secondary clarification are similar to those for primary sedimentation. Since the same mechanism is involved for both processes, the similar effects are expected. It has been assumed that the capacity requirement figures for primary sedimentation apply for secondary clarification as well. The benefits are computed by considering capital, operating, and maintenance costs and the resultant savings are given below:

Table 14

COST SAVINGS FOR SECONDARY CLARIFICATION
(heat transfer costs excluded)

COST SAVINGS IN CENTS/1000 GAL	TREATMENT PLANT CAPACITY (MGD)		
	1	10	100
New Plants	0.34-0.44	0.50-0.66	0.36-0.47
Existing Plants	0.28-0.48	0.41-0.73	0.30-0.52

DISINFECTION

As indicated in Section IX, the two possible benefits of increased temperature operation on disinfection are lower chlorine requirements and smaller contact chambers. This is a tradeoff situation whereby for the same contact time less chlorine is required or at the same chlorine dosage rate less contact time is required. Each of these alternatives must be studied to see which offers the greatest advantage.

An examination of Fig. 12 reveals that operation at a temperature level increase of 10 C can yield a savings in chlorine usage of from 39 to 66% or a savings in contact time of 31%. The chlorine dosage savings calculation is based on a normal input of 8 mg/l of chlorine recommended for an activated sludge plant.[77] All of these calculations are for the indirect heat transfer method only since the use of direct heat transfer would result in additional dilution of the chlorine and more total chlorine would be required.

These benefits identified can be converted to cost figures by considering chlorine costs and the costs for equipment, operation, and maintenance in a disinfection facility. The savings for this process are given below:

Table 15

COST SAVINGS FOR DISINFECTION
(heat transfer costs excluded)

COST SAVINGS IN CENTS/1000 GAL	TREATMENT PLANT CAPACITY (MGD)		
	1	10	100
Chlorine savings	0.20-0.33	0.20-0.33	0.20-0.33
Contact chamber savings	0.22	0.12	0.06

From this table it appears that the best approach is to take the chlorine savings. Since the contact chamber savings are competitive, at least for the lower capacity plants, a decision for a particular plant would rest upon the actual chlorine demand for the wastewater being treated and the design features of the disinfection facilities.

ACTIVATED SLUDGE PROCESS

The temperature effects on activated sludge have been discussed in Section X. It appears that operation at higher temperature can yield higher removal efficiencies provided the higher temperature is not above the optimum of about 26 C. From Fig. 16 it can be seen that BOD removal increases from 82 to 91% when changing the operating temperature from 10 C to 20 C. As for sedimentation, this removal efficiency increase could be used to permit lower capacity units for new plants or to save in additional capacity which would otherwise have to be added to existing plants. Figure 14 provides the type of information needed to make calculations such as: (1) the reduced detention time (and corresponding capacity) possible in operating at the same BOD removal level, but at higher temperatures; and (2) the increased detention time required in

operating at the same temperature, but higher BOD removal rate. The results of such calculations for activated sludge are given below:

Table 16

EFFECTS OF WASTE HEAT UTILIZATION ON ACTIVATED SLUDGE

	NEW PLANTS	EXISTING PLANTS
Capacity required without waste heat use	1.00	1.30-1.37
Capacity required with use of waste heat (Indirect heat transfer: 10 C rise)	0.72-0.77	1.0

These benefits are quantified by a consideration of capital, operating, and maintenance costs. The resultant savings are given below:

Table 17

COST SAVINGS FOR ACTIVATED SLUDGE
(heat transfer costs not included)

COST SAVINGS IN CENTS/1000 GAL	TREATMENT PLANT CAPACITY (MGD)		
	1	10	100
New Plants	0.48-0.58	0.32-0.40	0.26-0.31
Existing Plants	0.62-0.77	0.43-0.52	0.34-0.41

NITRIFICATION

The temperature effects on nitrification have also been discussed in Section IX and were found to be intimately associated with the activated sludge process. Operation at higher temperatures gives higher process efficiencies. Table 18 indicates that at elevated temperatures lower aeration volumes and lower oxygen requirements can be used for nitrification. Based on this information, the following can be calculated: (1) the reduced processing capacity possible in operating at a higher temperature, but yielding the same level of nitrification; and (2) the increased capacity necessary to operate at the same temperature, but yielding a higher level of nitrification.

Table 18

EFFECTS OF WASTE HEAT UTILIZATION ON NITRIFICATION

	NEW PLANTS	EXISTING PLANTS
Capacity required without waste heat use	1.00	1.89
Capacity required with use of waste heat (Indirect heat transfer: 10 C rise)	0.53	1.00

In addition to the savings associated with unit capacities as outlined above, savings in compressor capital costs and compressor operating costs are possible due to the lower oxygen requirements. Both of these benefits are quantified by a consideration of capital, operating, and maintenance costs. The resultant savings are shown in Table 19.

Table 19

COST SAVINGS FOR NITRIFICATION*
(heat transfer costs not included)

COST SAVINGS IN CENTS/1000 GAL	TREATMENT PLANT CAPACITY (MGD)		
	1	10	100
New Plants	0.97-0.98	0.65-0.67	0.52-0.53
Existing Plants	1.8-2.4	1.2-1.3	0.82-1.0

*It is recognized that nitrification and the activated sludge process take place in the same equipment. Costs savings for waste heat utilization in activated sludge have already been calculated and the savings shown here are only the additional incremental savings in the system for the nitrification portion of the process.

VACUUM FILTRATION

Increased temperature has the effect of reducing the filtration area required in filtering sludges, as discussed in Section IX. An increase of 10 C gives an 11.6% reduction in filtration area. This results directly in reduced filtration equipment and reduced associated operating and maintenance costs. The savings for various treatment plant sizes are shown below:

Table 20

EFFECTS ON VACUUM FILTRATION
(heat transfer costs not included)

	TREATMENT PLANT CAPACITY (MGD)		
	1	10	100
Cost savings, cents/1000 gal	0.32	0.31	0.23

OVERALL COST SAVINGS

If the waste heat is utilized in warming the wastewater before primary clarification, the benefits of operation at higher temperature are gained throughout the entire plant. Benefits for each of the processes can, therefore, be added together to obtain the overall cost savings. The resultant savings are given below:

Table 21

OVERALL COST SAVINGS FOR SECONDARY TREATMENT PLANT
(heat transfer costs excluded)

COST SAVINGS IN CENTS/1000 GAL		TREATMENT PLANT CAPACITY (MGD)		
		1	10	100
New plants	without nitrification	1.54-1.90	1.52-1.95	1.27-1.61
Existing plants	without nitrification	1.59-2.15	1.51-2.06	1.26-1.78
New plants	with nitrification	2.51-2.88	2.17-2.62	1.79-2.14
Existing plants	with nitrification	3.39-4.55	2.71-3.36	2.07-2.78

BENEFIT/COST ANALYSIS

The benefits of using waste heat can now be compared with the heat transfer costs derived in Section XI. The first comparison is for the case where the waste heat is available directly at the treatment plant, such as for a combined utility or where heat transport involves no cost. Heat transfer costs are taken from Section XI. The overall benefits and costs for this case are plotted on Fig. 17. From this figure it is

seen that benefits exceed costs for treatment plants with a capacity greater than 5 MGD. Depending on the design details of the particular plant, waste heat utilization may also be advantageous for plants with capacities between 2 and 5 MGD.

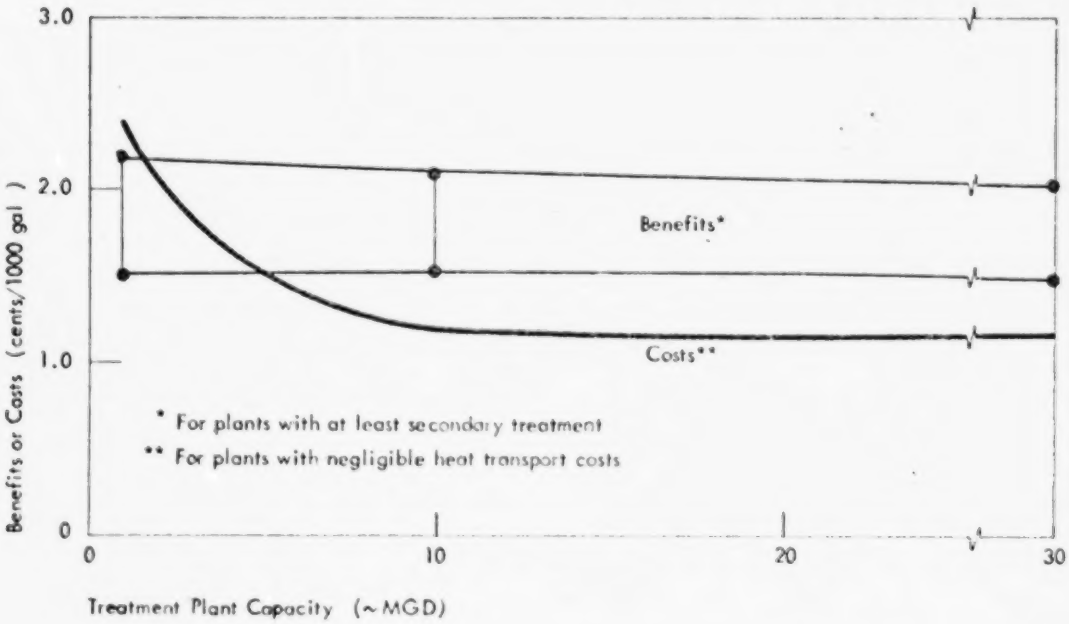


Fig. 17. Benefits and Costs for Various Treatment Plant Capacities

Where heat transport costs must be considered, the figures from Table 10, "Overall Heat Transfer Costs," in Section XI can be used. For this case, it appears that the benefits exceed costs for treatment plants of 5 MGD capacity or greater only when the waste heat must be transported for distances of less than about a half mile.

The above discussions are all applicable for a 10 C rise in wastewater temperature and for a final temperature of no more than 30 C. This temperature increase corresponds to the average which could be expected in using power plant cooling water. Areas where a higher temperature utility water were available are not so numerous, but the benefits from waste heat utilization in such areas are greater. It appears that if a 10 C rise could be obtained (and for final temperatures below 30 C), the following overall effects would apply:

1. Benefits exceed costs for all size treatment plants where heat transport costs are negligible

2. For 10 MGD plants, waste heat utilization is economic for heat transport distances up to about 2-1/2 miles

3. For 100 MGD plants, it is economic for distances up to about 4-1/2 miles.

Another potential benefit of waste heat utilization in treatment plants is the reduction of the thermal shock mixing zone to receiving waters. Without utilization, the power plant hot water is discharged to the local receiving water at about 10 C above ambient. With utilization, the power plant effluent can be used for heat transfer and then mixed with the treatment plant effluent to result in a combined discharge to the local receiving water at no more than 8 C above ambient (some heat losses will occur in the treatment plant, so this temperature will be somewhat lower in practice). This benefit has not been quantified since a calculation of cost savings would depend on the thermal standards of the local area, heat losses in the treatment plant, and the method of heat dissipation being used by the power plant. Once again it must be indicated that the total heat load on the receiving water may be unchanged (or only very slightly lowered). This is most easily illustrated by Fig. 18, showing the two cases with and without waste heat utilization. In the upper case (no heat use), the river water (at the upstream temperature, T_u) passes through the treatment plant and discharges at essentially the same temperature. The same water passes through the power plant and discharges at a higher temperature (T_h). This results in a certain thermal shock when this stream reaches the river and yields an elevated downstream river temperature, T_d. In the lower case (with heat use), the river water still feeds both plants. In this case, however, the power plant effluent heats the treatment plant influent and later mixes with the treatment plant effluent. The final discharge to the river is now at a lower temperature (T_m). This results in a lesser thermal shock when this stream reaches the river, although the downstream river temperature may be the same as for the upper case, T_d. Whatever heat is lost from the elevated temperature wastewater in the lower case (H_2) as it passes through the treatment plant will subtract from the heat load on the river, but add to the heat load in the atmosphere.

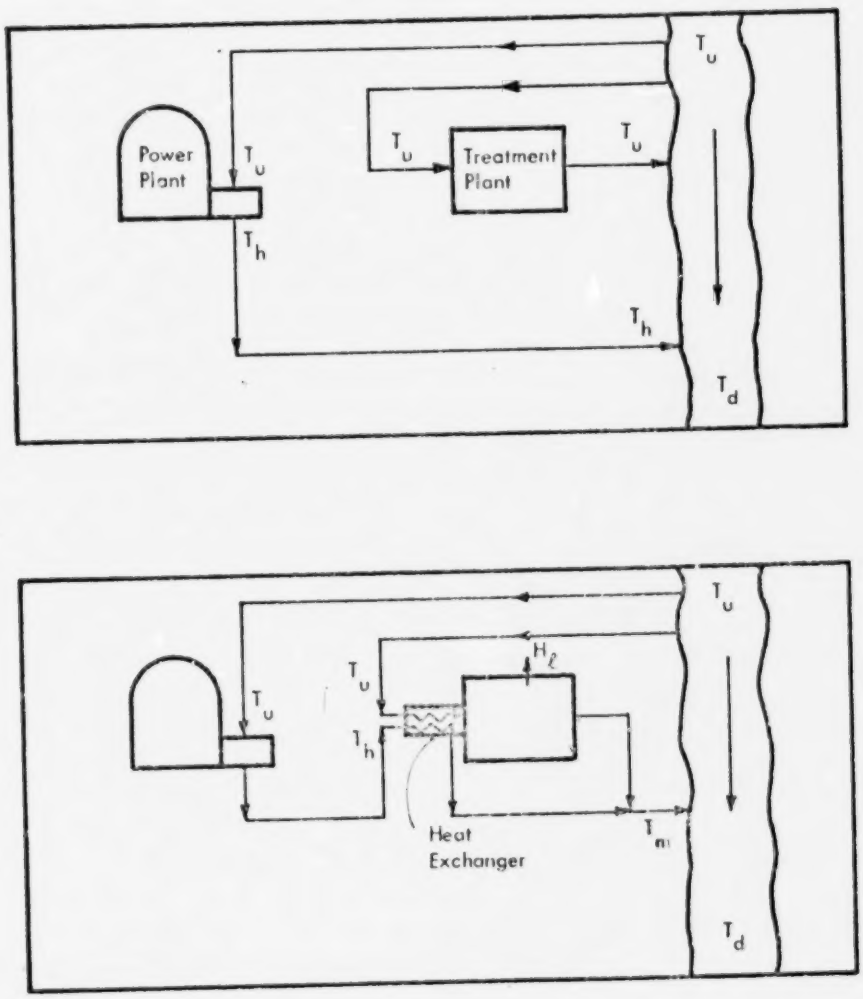


Fig. 18. Temperature Distribution in Waste Heat Utilization

SECTION XIII

TEMPERATURE EFFECTS ON ADVANCED WASTE TREATMENT PROCESSES

In this section, each of the candidate advanced waste treatment processes will be examined to determine the performance characteristics at various temperature levels. Wherever appropriate, temperature limitations and anticipated problems at elevated temperatures will be identified.

REVERSE OSMOSIS

In reverse osmosis treatment, the wastewater is pumped under pressure into a membrane assembly. Purified water passes through the membrane and the concentrated brine (with impurities) is rejected by the membrane. The most important thermal effect on such a system is that operation above a reference temperature yields a higher product water flux rate through the membrane. This means that increasing the temperature results in a smaller membrane area required to produce a specified produce water rate and quality. This effect is expressed quantitatively[125] by saying that the required membrane area decreases 3.2% for every degree Centigrade above a reference temperature for the same amount of product water.

Current reverse osmosis membranes are subject to performance degradation by hydrolysis. Hydrolysis increases with increasing temperature and 38 C is generally taken as the limiting operating temperature. Even below 38 C, the increased hydrolysis at elevated temperatures results in a poorer effluent and a shorter membrane life with corresponding increased replacement and maintenance costs.

ACTIVATED CARBON ADSORPTION

The subject of temperature effects on adsorption is very complex and the results of experiments in this field are somewhat confusing. It appears[76] that the adsorption of some materials is increased with increasing temperature while other materials show decreased adsorption. In addition, the direction of the change in adsorption for some materials with temperature change depends on the type of activated carbon utilized.

Detailed studies[2] with adsorbing biochemically resistant materials provide an insight into this confusion. Experimental work[2] shows that adsorption rate increases with increasing temperature. The time to reach equilibrium is a variable, depending on the material being

adsorbed, and may range from weeks to months. Other experimental work[2] shows that adsorption at lower temperatures tends to approach equilibrium more slowly and the equilibrium value of adsorption capacity is greater. In summary, adsorption at a temperature above a reference level takes place more rapidly and approaches equilibrium sooner, although the equilibrium value of adsorption capacity is lower.

In an actual treatment system, true equilibrium may never be reached and small differences in equilibrium adsorption capacity, therefore, may be of no importance. Another possibility is that the lower capacity at elevated temperature operation (which could require more frequent regeneration of the carbon) may be more than compensated for by the higher quality effluent resulting from the higher adsorption rates. An examination of experimental data in the literature[76] reveals that in the range from about 10 to 30 C, an increase in temperature of 10 C gives an 8% reduction in equilibrium adsorption capacity, but a 36% increase in initial adsorption rate.

ION EXCHANGE

Temperature effects on ion exchange processes are also very complex.[73] Whereas the dependence of adsorption on temperatures has not yet been studied systematically, theory indicates that highly specific adsorption decreases with increasing temperature. The effect of temperature on exchange selectivity seems to depend on the specific ion involved. Some ions, such as sodium, potassium, and barium, have decreased selectivity at higher temperatures, while other ions, such as zinc, cobalt, and beryllium, have increased selectivity. Ion-exchange rates increase with increasing temperatures, depending on whether particle diffusion control applies (where a 4 to 8% increase per degree Centigrade is possible) or film diffusion control (3 to 5% increase per degree Centigrade). Elevated temperatures may be impractical for use if temperature-sensitive ion-exchange resins and/or chemicals (e.g., ammonia) are utilized.

AMMONIA STRIPPING

Ammonia stripping basically involves blowing air through wastewater to transfer dissolved ammonia from the water into the gas phase. Raising the temperature of the wastewater has the effect of making the ammonia less soluble and more easily removed. This reduction in the solubility of ammonia vs temperature is indicated in Table 22.

Table 22

SOLUBILITY OF AMMONIA IN WATER

TEMPERATURE (C)	SOLUBILITY (parts ammonia/ 100 parts water)
0	88
10	69
20	53
30	41
40	32
50	23

The concentration of ammonia in typical wastewaters, however, is on the order of 25 mg/l (or 0.0025 parts/100 parts water) and the solubility reductions of the above table would be of little use in increasing stripping efficiency.

Increasing wastewater temperature also has the effect of increasing the partial pressure of ammonia which promotes removal. An increase of 10 C in the range of 0 to 50 C results in an increased ammonia partial pressure of from 59 to 80%. A stripping operation at elevated temperature should, therefore, be capable of a higher rate of ammonia removal for the same air flow rate or the same ammonia removal for a lower air flow rate (assuming the stripping air can effectively remove the higher quantities of ammonia in the vapor phase due to increased vapor pressure).

Since ammonia stripping does involve blowing ambient air through the wastewater, this process is vulnerable to problems of freezing during cold weather. Heating the wastewater would permit operation of the stripping unit during periods when the weather would normally force the unit to be inoperative. Heating the stripping air could also be done in this case, but this is a more expensive method (especially if the heated wastewater was already used in previous operations). Use of heated air or water would have the added advantage of reducing possible calcium carbonate fouling in winter.

BIOLOGICAL DENITRIFICATION

This is basically an anaerobic process in which the nitrate ion is metabolized by microorganisms to nitrogen gas. Since it is a biological process, it is expected that increasing temperature will increase

metabolic action and denitrification. A recent study[109] showed denitrification rates of 0.30 and 0.68 mg/hr per gm of MLVSS for 18 and 29 C, respectively. This is equivalent to a rate increase of 12% per degree C temperature increase which should be applicable at least over the region from 15 to 30 C.

Biological denitrification systems operated at elevated temperatures should, therefore, be capable of greater removal efficiencies for the same flow rates or could yield similar removal efficiencies for higher flow rates.

PHOSPHORUS REMOVAL BY PRECIPITATION

This process involves the addition of chemicals to wastewater which react with the phosphorus to yield insoluble phosphates. A wide variety of chemicals have been tried (such as lime, iron salts, aluminum salts, and lanthanum)[13,17,127,128] and the point of chemical addition can be anywhere in the treatment train (primary, secondary, or tertiary).[3]

Elevated temperatures could be beneficial in phosphorus removal by increasing the chemical reaction rate or by shifting the equilibrium to favor increased phosphorus removal. A study[127] of temperature effects using aluminum and iron salts shows, however, that reaction temperature appears to have no effect on the rate or extent of phosphorus removal.

Elevated temperatures could also be useful in speeding the sedimentation of the precipitates for this process just as for suspended solids in normal sedimentation. This benefit of higher temperature will not have much effect on overall phosphorus removal efficiencies since systems are currently designed to operate at 85 to 95% removal, but the more rapid sedimentation will reduce required detention times which means that smaller sedimentation tanks can be used. Assuming that the precipitates in phosphorus removal respond in a similar manner to suspended solids in conventional wastewater treatment sedimentation, Fig. 6 of Section IX can be used to estimate reductions in detention time. From Fig. 6, an increase of 10 C results in detention time reductions on the order of 15 to 25%. On this basis, sedimentation tanks in a phosphorus removal system could be 15 to 25% smaller for a 10 C temperature increase.

SECTION XIV

HEAT TRANSFER BENEFITS FOR ADVANCED WASTE TREATMENT PROCESSES

As for the normal biological treatment processes, benefits for advanced treatment processes due to waste heat application are expressed as savings in cents/1000 gal treated. Each of the processes will be examined in the following paragraphs to determine benefits on an individual basis. The overall benefits for a specific plant will depend on which processes are incorporated into the plant and which ones have the increased temperature.

REVERSE OSMOSIS

Required membrane area for a given capacity is reduced 3.2% for every degree Centigrade increase, as shown in Section XIII. For the 10 C rise taken as a standard for this study, the net membrane reduction is 32.4%. With this benefit value, the savings in capital, operating and maintenance costs for reverse osmosis can be calculated.[50,124] The results are given below:

Table 23

BENEFITS FOR REVERSE OSMOSIS
(heat transfer costs excluded)

	TREATMENT PLANT CAPACITY (MGD)		
	1	10	50
Savings in cents/1000 gal	9.4	7.3	6.1

*This is the maximum size reverse osmosis plant for which costs have been estimated.[119]

Heat transfer costs are shown in Table 9 of Section XI. A comparison of benefits and costs shows that waste heat utilization is economical for all size treatment plants using reverse osmosis where there are no heat transport costs (as for a combined utility complex). Where the waste heat must be transported from a distance, utilization is still economical under the following conditions:

1. For 1 MGD plants where the distance is no more than 3-1/2 miles

2. For 10 MGD plants and distances up to 14 miles

3. For 50 MGD plants and distances up to 13 miles.

It must be remembered that elevated temperature operation of reverse osmosis also yields a somewhat poorer effluent and lower membrane life.

ACTIVATED CARBON ADSORPTION

From Section XIII, a 10 C increase in wastewater temperature was seen to result in a 36% increase in adsorption rate but an 8% reduction in adsorption capacity. It can be assumed that the increased adsorption rate permits a smaller capacity adsorption unit to achieve the same effluent quality. The lower adsorption capacity will require more frequent regeneration. These two conflicting factors must be evaluated in terms of capital, operating, and maintenance costs[3,143] to determine the possible benefits of waste heat utilization. The results of this evaluation are given below:

Table 24

BENEFITS FOR CARBON ADSORPTION
(heat transfer costs not included)

	TREATMENT PLANT CAPACITY (MGD)		
	1	10	100
Savings in cents/1000 gal	3.60	1.80	0.86

A comparison of these savings with heat transfer costs reveals that benefits exceed costs for waste heat use in carbon adsorption only for plants with capacities less than about 60 MGD and where there are no heat transport costs. Where heat transport costs must be considered, plants in the range of from 1 to 10 MGD capacity can economically utilize waste heat only where distances are less than about one-half mile.

ION EXCHANGE

Ion-exchange rates increase from 3 to 8% per degree Centigrade with increasing temperature, as indicated in Section XIII. The assumed standard of 10 C rise yields increased rates of from 30 to 80%. The rates can be equated to smaller exchange units to achieve the same

quality effluent. By considering costs for ion exchange,[3] savings resulting from waste heat utilization can be calculated. The results of these calculations are given below:

Table 25

BENEFITS FOR ION EXCHANGE
(heat transfer costs excluded)

	TREATMENT PLANT CAPACITY (MGD)	
	1	10
Savings in cents/1000 gal	1.6-3.1	0.8-1.5

A comparison of benefits and costs indicates that waste heat utilization could be economical for ion exchange units of from 1 to 10 MGD capacity and where the waste heat must be transported no more than about one-quarter mile. These savings would probably represent upper limits since temperature effects for ion exchange processes are not fully defined.

AMMONIA STRIPPING

From Section XIII, the 10 C wastewater temperature increase appeared to increase ammonia removal efficiency from 50 to 80%. Results of actual plant operation at different temperatures[39] show that to yield the same quality effluent, the 10 C rise permits the use of small stripping units (from 53 to 67% of normal size). With this information and a review of capital, operating, and maintenance costs for ammonia stripping[3,39,143] benefits of waste heat utilization can be determined. The resultant savings are given below:

Table 26

BENEFITS FOR AMMONIA STRIPPING
(excluding heat transfer costs)

	TREATMENT PLANT CAPACITY (MGD)		
	1	10	100
Savings in cents/1000 gal	1.1-1.5	0.5-0.7	0.5-0.7

A comparison of these savings with costs reveals that waste heat utilization for ammonia stripping alone is not an economical process. Where ammonia stripping is used in conjunction with other processes, however, the savings of stripping can be added to the savings from the other processes.

BIOLOGICAL DENITRIFICATION

The denitrification rate is increased 12% per degree Centigrade temperature increase, as shown in Section XIII. This will yield a 120% rate increase for the standard 10 C rise. On this basis, the denitrification chamber capacity can be reduced to about 45% of normal size and still produce the same quality effluent. Costing information on denitrification is not abundant, but a recent report[3] indicates that the capital cost of such a system would be about 25% greater than for a conventional activated sludge process of the same flow. The denitrification chamber accounts for only about 20% of the total in this overall nitrification/denitrification system. A consideration of activated sludge process costs permits an estimation of the benefits for denitrification due to waste heat utilization as shown below:

Table 27

BENEFITS FOR DENITRIFICATION
(heat transfer costs not included)

	TREATMENT PLANT SIZE (MGD)		
	1	10	100
Savings in cents/1000 gal	0.12	0.08	0.07

Comparing benefits and costs reveals that waste heat use for denitrification alone is not economical. Since this process is used in combination with others, however, the benefits can be added to those of the other processes.

PHOSPHORUS REMOVAL BY PRECIPITATION

From Section XIII it was seen that sedimentation tanks in a phosphorus removal system could be 15 to 25% smaller for a 10 C increase. With this range of benefits and a consideration of precipitation costs[3] in a two-clarifier process, savings can be calculated. The results are:

Table 28

BENEFITS FOR PHOSPHORUS REMOVAL
(heat transfer costs not included)

	TREATMENT PLANT CAPACITY (MGD)		
	1	10	100
Savings in cents/1000 gal	0.76-1.13	0.49-0.70	0.37-0.52

Comparing benefits and costs shows that phosphorus removal alone does not show promise in profiting from waste heat utilization, but the savings of this process should be considered in a system combining many processes.

BENEFIT/COST ANALYSIS

The benefits derived above can now be compared with the heat transfer costs of Section XI. The first comparison is for the case of a combined utility where heat transport costs are negligible and where the process is considered by itself. It appears that benefits exceed costs for all sized reverse osmosis plants, for carbon adsorption plants up to 60 MGD, and for ion-exchange plants up to 10 MGD. Costs exceed benefits for ammonia stripping, denitrification, and phosphate removal. The second comparison is for the case of heat transport distances of a mile or more, and again, where the process is considered by itself. In this case reverse osmosis alone is favorable and for distances of up to 14 miles of heat transport. The final comparison is for the case of the process considered as an adjunct to a secondary treatment plant. In this case, all processes are favorable since positive benefits are apparent for each and the heat transfer costs have already been charged to the secondary plant (no additional costs are required if the effluent from the secondary plant is already heated).

SECTION XV

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support and guidance given by personnel from the Federal Water Quality Administration, specifically Mr. Gerald Stern, who served as Project Monitor, and Dr. Robert Smith and Dr. James Smith of the Taft Research Center.

Appendix A

COLD REGION CITIES

WASTEWATER TREATMENT PROJECT

U.S. cities with population of 100,000 or more and average January temperature of less than 30 F.

CITY	1970 POPULATION (Preliminary)	AVERAGE TEMPERATURE FAHRENHEIT, JANUARY	ANNUAL AVERAGE TEMPERATURE	MEAN NUMBER OF DAYS MIN. TEMP. 32 F OR LESS
Minnesota				
Duluth	99,761	8.7	37.9	187
Minneapolis	431,977	22.4	43.7	160
St. Paul	308,686	22.4	43.7	160
Iowa				
Cedar Rapids	109,111	-	-	-
Des Moines	198,427	19.9	49.2	140
Wisconsin				
Madison	170,073	9-26	-	-
Milwaukee	709,537	20.6	45.1	147
Illinois				
Chicago	3,322,855	26.0	50.8	117
Peoria	125,736	25.7	51.4	131
Rockford	144,707	-	-	-
Indiana				
Fort Wayne	175,083	-	-	-
Gary	174,132	-	-	-
Hammond	107,108	-	-	-
Indianapolis	742,613	29.1	52.1	120
South Bend	122,797	-	-	-
Michigan				
Detroit	1,493,914	26.9	50.1	125
Flint	193,571	-	-	-

CITY	1970 POPULATION (Preliminary)	AVERAGE TEMPERATURE FAHRENHEIT, JANUARY	ANNUAL AVERAGE TEMPERATURE	MEAN NUMBER OF DAYS MIN. TEMP. 32 F OR LESS
Michigan (Cont'd)				
Grand Rapids	195,892	24	-	-
Lansing	129,021	-	-	-
Livonia	109,746	-	-	-
Ann Arbor	98,414	-	-	-
Dearborn	103,870	-	-	-
Warren	179,217	-	-	-
Ohio				
Akron	273,266	-	-	-
Canton	108,872	-	-	-
Cleveland	738,956	28.4	49.7	128
Columbus	533,418	29.9	52.0	123
Dayton	239,591	-	-	-
Parma	99,691	-	-	-
Toledo	379,104	-	-	-
Youngstown	139,903	-	-	-
New York				
Albany	113,857	22.7	47.6	146
Buffalo	457,808	24.5	46.7	137
Rochester	293,695	-	-	-
Syracuse	192,529	24	-	-
Yonkers	204,789	-	-	-
Utica	90,802	-	-	-
Pennsylvania				
Allentown	108,926	-	-	-
Erie	125,941	-	-	-
Pittsburgh	512,789	28.9	50.3	127
Scranton	102,294	-	-	-

CITY	1970 POPULATION (Preliminary	AVERAGE TEMPERATURE FAHRENHEIT JANUARY	ANNUAL AVERAGE TEMPERATURE	MEAN NUMBER OF DAYS MIN. TEMP. 32 F OR LESS
Connecticut				
Bridgeport	155,359	-	-	-
Hartford	155,868	26.0	49.8	138
New Haven	133,543	30	-	-
Stamford	107,907	-	-	-
Waterbury	106,431	-	-	-
Massachusetts				
Boston	628,215	29.9	51.4	94
Cambridge	98,942	-	-	-
New Bedford	101,262	-	-	-
Worcester	175,140	-	-	-
Springfield	162,078	-	-	-
Rhode Island				
Providence	176,920	29.2	50.1	124
South Dakota				
Sioux Falls	72,557	15.2	45.7	174
Nebraska				
Lincoln	148,092	-	-	-
Omaha	327,789	22.3	51.5	136
Kansas				
Kansas City	166,682	-	-	-
Topeka	123,043	-	-	-
Utah				
Salt Lake City	176,793	27.2	50.9	141
Nevada				
Reno	72,121	30.4	48.4	191

CITY	1970 POPULATION (Preliminary)	AVERAGE TEMPERATURE FAHRENHEIT JANUARY	ANNUAL AVERAGE TEMPERATURE	MEAN NUMBER OF DAYS MIN. TEMP. 32 F OR LESS.
Colorado				
Colorado Springs	124,856	-	-	-
Denver	512,691	28.5	49.5	164
Pueblo	96,403	-	-	-
Lakewood	93,403	-	-	-
Washington				
Spokane	168,654	25.3	47.8	138
Idaho				
Boise	73,330	29.1	51.0	127

Sources of information:

1970 Census of Population, Preliminary Reports, Bureau of the Census, U.S. Department of Commerce.

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MONTH
WEEK

November				December				1970 January				1971 February				April			
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

SPECIAL INFORMATION

Activated Sludge Unit
(check one)

mg/l ☐ lbs/day ☐

1. M.L.S.S.
2. pH
3. Daily Oxygen Use
   (check one)
   - lbs ox./lbs BOD ☐
   - cu.ft./min. ☐
   - lbs/day ☐
4. Influent to Activated
   Sludge (check one)
   - mg/l ☐ lbs/day ☐
   - Total Solids (T.S.) ☐
   - Volatile Suspended Solids
     (V.S.S.) ☐
5. Aerated Suspended Solids
   (check one)
   - mg/l ☐ lbs/day ☐
   - V.S.S. ☐
   - T.S. ☐
6. Total Activated Sludge Units
   - Volume cu.ft. _____
7. Average Depth of Units ____

_____

COMMENTS

MONTH
WEEK

PLANT FLOW
(check one)

MGD ☐
GPM ☐
Cf.S ☐

1. Average Daily Flow
2. Peak Daily Flow
3. Recycle Flow

BIOLOGICAL LOADING
(check one)

mg/l ☐ lbs/day ☐

1. Plant Influent
   - BOD
   - COD
   - Suspended Solids (S.S.)
2. Primary Clarifier Effluent
   - BOD
   - COD
   - S.S.
3. Activated Sludge Unit or Trickling Filter Effluent
   - BOD
   - COD
   - S.S.
4. Secondary Clarifier

   Recycle
   - BOD
   - COD
   - S.S.

   Final Effluent
   - BOD
   - COD
   - S.S.

November				December				1970 January				1971 February				April			
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

MONTH November December 1970 January 1971 February April

WEEK 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4

OPERATIONAL PLANT UNITS (check)

1. Grit Chamber ☐
2. Primary Clarifier ☐
3. Activated Sludge Units ☐
4. Trickling Filters
   - Standard ☐
   - High Rate ☐
5. Secondary Clarifier ☐
6. Lagoons ☐
7. Chlorination Units ☐

Date of Plant Construction _____

Date of New Plant Units _____

Give average values for following parameters (F^{o} or C^{o})

PHYSICAL PARAMETERS

1. Ambient Air
2. Primary Clarifier
3. Activated Sludge or Trickling Filter
4. Secondary Clarifier
5. Lagoons
6. Chlorination Unit

Appendix B

REFERENCES

REFERENCES

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Appendix C

COMPUTER PROGRAM FOR
ACTIVATED SLUDGE MODEL
In Super Basic

APPENDIX C

Statements

```
100  FOR A = 5
110  FOR N = 1, 0.5, 0.125, 0.0625
200  PRINT,
210  PRINT,
220  PRINT "N"., N,
300  FOR T = 1, 16 to 31 Step 5,
400  P = 1 - 10 ↓ A* (N* (1.047) ↓ (T-20)),
500  PRINT T, P,
600  NEXT T,
700  NEXT N,
800  END
```

Appendix D

SAMPLE CALCULATIONS

APPENDIX D

SAMPLE CALCULATIONS

This appendix presents sample calculations appropriate to the computation of heat losses and heat transfer costs which are given in Sections VIII, XI and XII.

HEAT LOSSES

The equations and calculations given here apply to heat losses in transportion water through pipes as reported in Section VIII. The appropriate derived equations are:

$$H = 0.0022a^{-0.2}V^{0.8} \tag{1}$$

where H is the heat transfer proportionality constant in

cal/cm^2 sec deg C,

a is the radius of the pipeline in cm, and

V is the water velocity in cm/sec.

$$\Phi = \frac{2Hl}{\left(1+\frac{aHln\ b/a}{K}\right) CaV} \tag{2}$$

where Φ is $\ln \frac{v^*o - v_1}{v^{**}o - v_1}$, in which v^*o and $v^{**}o$ are the water temperature of the pipeline, and v_1 is the air temperature (all in deg C),

l is the pipeline length in cm,

b is the depth of the pipeline in cm,

ρ is the water density in cm/cm^3,

C is the heat capacity of water in cal/gm deg C, and

K is the thermal conductivity of the soil in which the pipeline is buried.

$$v^{**}o - v_1 = \left(v^*o - v_1\right)\rho^{-\Phi} \tag{3}$$

In the basic case, the pipeline has a 4-in diameter (which converts to a radius of 5.08 cm) and the flow rate is 1 MGD (which converts to a velocity in the pipeline of 541 cm/sec). Using equation (1), we find:

$$H = 0.0022(5.08)^{-0.2}(541)^{0.8}, \text{ or}$$

$$H = 0.246.$$

The basic case also examines a pipeline length of one mile (161,000 cm) and a depth below the surface of 6 ft (183 cm). Using equation (2), we find:

$$\Phi = \frac{(2)(0.246)(161,000)}{\left(1 + \frac{(5.08)(0.246)\ln(183/5.08)}{0.0023}\right)(1.0)(1.0)(5.08)(541)}, \text{ or}$$

$$\Phi = 0.0148$$

Finally, the basic case is also for an initial water temperature of 15 C and an air temperature of 5 C. Using equation (3), we find:

$$v^{**}o - 5 = (15 - 5)\rho^{-\Phi}, \text{ or}$$

$$v^{**}o = \frac{10}{\rho^{\Phi}} + 5, \text{ or}$$

$$v^{**}o = 14.9 \text{ C}.$$

Under these conditions, the water has dropped 0.1 C during transport through the pipeline.

HEAT TRANSFER COSTS

The specific samples given here apply to heat transport costs as reported in Table 9 of Section XI. Costs are presented in cents/1000 gal for treatment plants of various capacities. The basic system considered is one wherein hot water from a power plant is transported to the treatment plant where wastewater is heated in a heat exchanger. Using a high efficiency plate-type heat exchanger, about 2.4 gal of hot water are required to heat 1.0 gal of wastewater to the desired temperature. On this basis, a 1 MGD treatment plant requires 2.4 MGD of hot water from a power plant.

CAPITAL COSTS

The simplest and minimum cost case is where a pipeline only is required to transport the water and no pumps or pumping are needed. Water pipeline costs are most conveniently computed by using the Office of Saline Water cost calculating report.[135] From this, pipeline costs were found to be $75,000 per mile as of December 1969. Correcting to 1971 by means of Engineering News-Record (ENR) construction cost indices, current pipeline costs are $91,500/mi (June 1971), as shown below:

ENR construction cost indices:

December 1969 - 825
June 1971 -1050

Construction cost figures:

December 1969 - $75,000/mi

June 1971 - $(75,000)\left(\frac{1040}{825}\right) = \$91,500/mi$

Using 4-1/2% interest over 25 years for debt retirement, the corresponding amortization factor is 0.0773 and the annual cost is therefore:

$(\$91,500)(0.0773) = \$\ 7,300/mi$

For a one-mile pipeline, annual capital cost is, therefore, $7,300 and for a 1 MGD treatment plant the unit costs are as shown below:

1 MGD = 1,000,000 gal/day or 365,000,000 gal/year

$$\frac{\$7,300/year}{365,000,000\ gal/year} = \$0.02/1000\ gal \text{ or } 2\ cents/1000\ gal.$$

OPERATING AND MAINTENANCE COSTS

The Office of Saline Water report[135] again supplies the most useful costing information. Labor costs for December 1969 are found to be 1.0 cents/1000 gal. Using U.S. Department of Labor cost indices, the updated labor cost is 1.1 cents/1000 gal (May 1971), as shown below:

Labor cost indices:

December 1969 - 3.21
May 1971 - 3.53

Labor cost figures:

December 1969 - 1.0 cent/1000 gal
May 1971 - $(1.0)\left(\frac{3.53}{3.21}\right) = 1.1$ cent/1000 gal.

Other operation and maintenance costs include payroll extras as well as general and administrative overhead. These costs amount to 0.2 and 0.4 cent/1000 gal respectively, as shown below:

Payroll extras taken as 15% of labor costs - $(0.15)(1.1) = 0.2$
General and administrative overhead taken as 30% of the combined labor plus payroll extras - $(0.30)(1.1 + 0.2) = 0.4$

TOTAL COSTS

The total costs are the summation of capital plus operating and maintenance costs. For this example of a 1 MGD treatment plant supplied by a one-mile pipeline, total costs amount to 2.0 + 1.1 + 0.2 + 0.4 or 3.7 cents/1000 gal. For other calculations, differences in capacity and additional equipment requirements must be taken into account. Also, where pumps are required costs for electric power in pumping must be included.

Appendix E

SAMPLE CALCULATIONS FOR TEMPERATURE EFFECTS ON NITRIFICATION PARAMETERS

APPENDIX E

SAMPLE CALCULATIONS FOR TEMPERATURE EFFECTS
ON NITRIFICATION PARAMETERS

Given:

Sludge age @ 15 C	= 5.5 days*
Flow	= 3 MGD
BOD_5	= 250 mg/l
NH_3N	= 25 mg/l
BOD removal	= 90%

and where

A	= 0.55
A'	= 0.40
b	= 0.20/day
X_V	= 3000 mg/l
G	= 5.5 days
X	= .6
S_r	= Flow x substrate (BOD_5 - NH_5N)
C	= 0.123/day
d	= 0.07/day

1. Required aeration volatile solids

$$Y = \frac{GaS_r}{(1 + GbX)} = \frac{(5.5)(0.55)(3 \times 225 \times 8.34)}{\left[1 + (5.5)(0.2)(0.6)\right]} = 10,900 \text{ lb}$$

2. Required aeration volume

$$V(ft^3) = \frac{Y}{X_V(8.34)(7.48)} \times 10^6 = \frac{10,900}{3000(7.48)} \times 10^6 = 5.82 \times 10^4 ft^3$$

3. Hydraulic retention time

$$t(hr) = \frac{V}{Flow} 24 = \frac{0.435}{3.0} 24 = 3.5 \text{ hr}$$

*See pp. , Ref. 1

4. Oxygen required in addition to that needed for carbonaceous oxidation

Nitrogen in influent:

Flow $\times 8.34 \times NH_3N = 3 \times 8.34 \times 25$ mg/l $= 625$ lb/day

Nitrogen in excess sludge:

$\Delta X_v = aS_r - bxY = 3080 - (0.2)(0.6)(10,900) = 1770$ lb/day

$N = 0.123(X)(\Delta X_v)/0.77 + 0.07\Delta'(\Delta X_v)/0.77$

$= 174 + 64 = 234$ lb/day

Net nitrogen to be oxidized = 625 - 234 lb/day

It requires 3.9 lb O_2 to oxidize 1 lb of NH_3-N

O_2 required = 391 3.9 = 1530 lb/day